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Robust and Sustainable Energy Pathways to Reach Mexico's Climate Goals

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A Dissertation Presented

by

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DEDICATION

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ABSTRACT

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As countries set climate change goals for adaptation and mitigation efforts, there are many questions regarding to how to reach these targets. These efforts will necessitate the transition of our electricity infrastructure from relying on conventional electricity generation technologies including natural gas, coal and oil, to clean energy generation with renewables. Through the three essays presented in this dissertation, we explore various pathways of development for the electricity system to reach long term climate change goals. We are interested in identifying: Is there a unique optimal development option or are there various? How do different mixes of electricity generation technologies affect the development of the electricity grid, transmission infrastructure, secondary infrastructure and sustainability? The goal of the dissertation is to present new insight to decision makers trying to develop future energy policy, to help facilitate reaching climate change goals and sustainable development. While this dissertation is focused on the Mexican electrical grid and climate change goals, the methodologies presented here can be applied more broadly to other electricity systems. In the first essay, we use a multi-model approach to study a series of development pathways to reach Mexico's 2050 climate change goals. We create expansion plans for the various development pathways with the use of a detailed model of the Mexican electrical grid. In the second essay, we develop optimal carbon capture and storage networks for each expansion plan that was presented in the first essay. We identify whether robust options exist within the carbon capture and storage network and what potential impacts the development of these networks could have on local communities. The third essay uses the results obtained from the previous essays to perform a comprehensive sustainability and equity analysis, with seven criteria, on the various development pathways for the electricity system. This analysis allows us to better understand the tradeoffs between the different development options and how they can impact questions of equity.

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INTRODUCTION

1.1 Objectives and Motivation

Mexico has set a series of ambitious greenhouse gas (GHG) emission goals in response to climate change concerns. Our research focuses on the implications these goals have on the development of Mexico's energy generation portfolio. We examine the generation expansion planning (GEP) problem in the Mexican Electrical Grid while considering national emissions goals. We evaluate expansion plans for reaching Mexico's emissions goals, while recognizing the difficulties of decision making under deep uncertainty that this problem presents. In this dissertation, an expansion plan refers to the expansions for generation, transmission and secondary systems over the planning period (2016-2050). Each expansion plan has its own production plan which dictates what generation plants are generating electricity and how much. From this, we identify robust policies and expansion pathways for the development of the electrical system.

This dissertation has three main goals: 1) investigate spatial implications, on transmission and installed capacity within the electrical grid, of top down pathways to reaching Mexico's national climate change goals, to identify robust pathways of development, 2) study what implications each expansion plan will have on carbon storage networks, and 3) incorporate multi criteria decision analysis (MCDA) to evaluate the sustainability and equity of various development pathways. Here we provide an overview of each of the three essays.

First Essay – We build off results from a previous paper [3] that uses integrated assessment models (IAM's) to study a series of pathways in which Mexico could reach its climate change goals for 2050. Integrated assessment models combine economic, energy, technology and climate models to study the impacts of different policies on climate change. Each IAM produced an optimal generation portfolio for the year 2050, for which we create an expansion plan within a detailed model of the Mexican electrical grid (PEGyT). These expansion plans created in the PEGyT model take into account information on transmission infrastructure as well as limitations on where generation technologies can be deployed. This extra layer of information in the PEGyT model, missing in the IAM's, helps us gain more insight on the validity of the results from IAM's and obtain useful, geographically detailed information for energy planning. From this analysis we identify critical areas of development for the electrical system which can be used to better inform the development of future energy policy.

Second Essay – Electricity systems that use carbon and capture technologies to reach climate change goals will need to develop networks for the transportation and permanent storage of CO_2. In this work we create carbon capture and storage networks with a cost minimization mixed integer linear programing (MILP) network expansion model for each of the expansion plans presented in the first essay. This model is applied to a system that consists of 32 nodes where CO_2 can potentially enter the system and 9 CO_2 storage sites. With the networks created by the network expansion model we analyze the results to identify robust investments and potential effects the various networks could have with indigenous or marginalized communities.

Third Essay – This study incorporates MCDA to evaluate the sustainability and equity of the expansion plans presented in the previous essays, considering a hypothetical decision makers' preference. MCDA allows us to better evaluate the tradeoffs among different sustainability criteria for each expansion plan by considering a set of social, environmental and economic factors. Novel contributions in this essay are that we will be studying entire expansion plans to the electricity system from 2016-2050 as well as incorporating geographic information into the sustainability evaluation of each scenario. We identify which expansion plans have the highest sustainability scores as well as what characteristics have the largest impact on the sustainability of the electrical grid.

For this study, we are collaborating with the National Institute for Electricity and Clean Energies in Mexico (INEEL). Using their Planning of Expansion of Generation and Transmission (PEGyT) model, used for studying generation and transmission expansion planning within the Mexican grid, we perform an in-depth analysis of the IAM portfolios shown in Figure 1. For each IAM generation portfolio we create an expansion plan, each of these developed within the limitations of the infrastructure and geographic distribution of natural resources within the Mexican electrical grid.

1.2 Background

Long-term climate change goals will require Mexico to make substantial changes in various sectors including electricity. As part of a larger study on the development of Latin American countries and their climate change goals, [3] investigated the different pathways in which Mexico could reach its climate change goals for the year 2050. This study used multiple Integrated Assessment Models (IAMs), which each produced an optimal electricity generation portfolio, Figure 1. While this generation portfolio information is useful at a high level, it does not provide information at a more practical level on how these portfolios might be achieved. In particular, it abstracts from the realities of geographical distribution and of the associated investment cost in energy infrastructure.

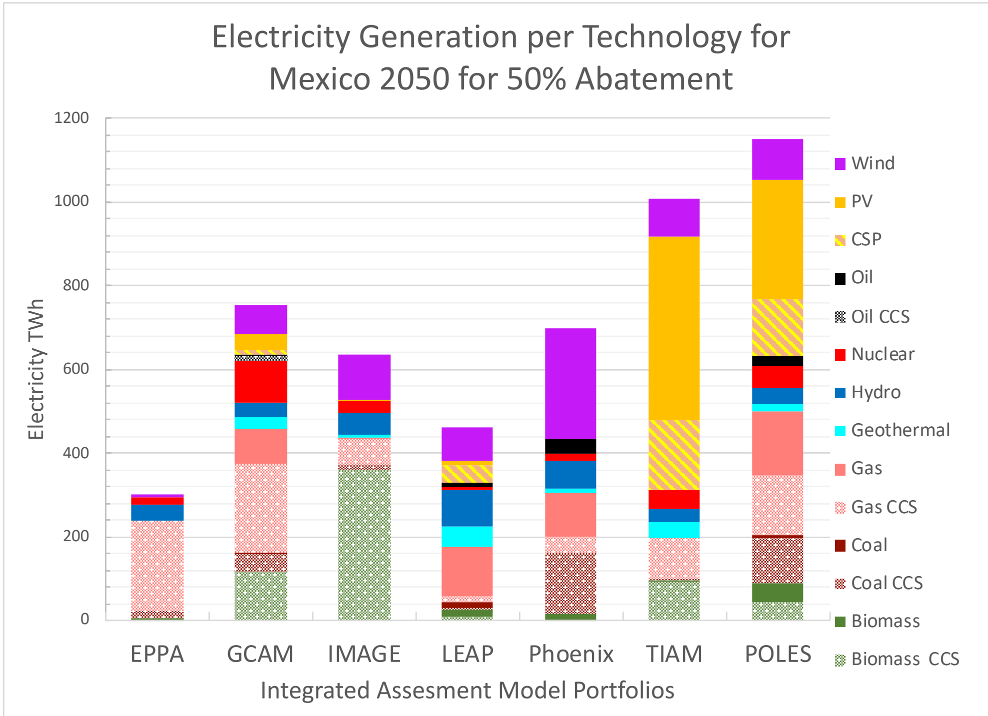


Figure 1. Electricity Generation by Technology and Scenario. Source: CLIMACAP-LAMP (2015)

In this section we will provide background information on the generation expansion planning problem, Mexico's climate change goals and Electrical Infrastructure in 2016, an overview on IAMs and an introduction to the PEGyT model.

1.2.1 Generation Expansion Planning (GEP)

The Generation Expansion Planning (GEP) problem aims to answer the following questions: What new generation capacity has to be installed in the system over the planning period to meet electricity demand at the least cost? What is the optimal time and location for new generation capacity to be added? Due to high overnight investment costs and long lead times in the energy sector, careful planning is especially important for countries to consider in order to avoid inefficiencies in their electricity system and investments. In recent years this has become an even more important problem with rising concerns of climate change, the importance of sustainability, and the decarbonization of the electrical system.

As illustrated by the various energy portfolios presented by the different IAMs in Figure 1 one of the main challenges in the GEP for long term planning is the deep uncertainty we face in assumptions for future scenarios regarding economic growth, technology development, electricity demand, fuel prices and on the effects of climate change. Another challenge comes from the growing desire to incorporate multiple and often conflicting objectives when looking at long term energy planning. This is especially common when looking at sustainability in the electricity system, which will be covered in essay 3.

GEP has been an active research area since the 1950s, where linear programming (LP) was used to approach this problem. This area is also one of the earliest applications of operations research. One of the first studies to successfully model the GEP as an LP problem was Masse and Gibart [21]. The GEP problem can be split into two main categories: single objective and multi objective optimization. Within single objective GEP it can be further classified into groups that model monopolies or competitive markets [46].

The GEP problem is generally expressed as a constrained non-linear discreet dynamic optimization problem. One of the most common algorithms used to approach this problem is dynamic programming, even though its application is limited due to the rate at which the complexity of this problem increases with every added variable. Due to the complexity of the GEP, including non-linearities, non-convexity and the large scale, many heuristic methods have also been used to solve this problem. Some of these techniques include genetic algorithms, improved genetic algorithms and evolutionary programming, which use similar principles of 'survival of the fittest' to obtain an optimal solution [47][48].

1.2.2 Climate Change Goals and Policies in Mexico

Mexico recognizes its vulnerability to the effects of climate change, including sea level rise, increasing average temperatures, more frequent extreme weather events and changes to the hydrological cycle. Preliminary assessments find that currently 13% of the country's municipalities have been identified as being highly vulnerable to climate change, mostly affecting lower income areas [9]. Because of these concerns Mexico has a vested interest in developing strategies for mitigation and adaptation to the negative effects of climate change.

Mexico's central policy to address climate change is the 2012 General Law on Climate Change (LGCC). The LGCC aims to help facilitate the development of climate change mitigation and adaptation efforts between government entities. This law created an institutional framework to help guide these efforts, creating the following entities [1]:

- The National Climate Change System (SINACC): Helps to coordinate efforts between the three different levels of government as well as efforts with the public, private and social sector.
- The Inter-Secretariat Commission on Climate Change (CICC): Meant to develop and implement national climate change policies, as well as coordinate and oversee the efforts of 14 different federal entities.
- The Council on Climate Change: A permanent entity meant to guide the CICC in the development of new policy. It is comprised of members from the private, academic and public sectors.
- The National Institute of Ecology and Climate Change (INECC): Mexico's research institute meant to coordinate and carry out scientific research on climate change.

In 2013 the National Climate Changes Strategy (ENCC) was developed to help guide future policy efforts by setting 10-20-40 year goals for the different sectors of society. The ENCC defines the pillars for the national policy on climate change for adaptation, mitigation and construction of new policy. The ENCC also addresses short lived climate pollutants (SLCP) particularly Black Carbon due to its impacts on air quality and adverse health effects [9].

On an international level, Mexico developed their Intended Nationally Determined Contributions (INDC) for the 2015 United Nations Climate Change Conference

(COP21) in Paris. The INDC for Mexico sets the country's goals for adaptation and mitigation efforts up to the year 2030. The mitigation section is divided into two sections: unconditional and conditional on the cooperation of the international community. The INDC was developed to keep in line with Mexico's long-term goal of 50% reduction by the year 2050 compared to 2000 levels. A novel aspect of Mexico's INDC is that fact that it addresses short lived climate pollutants as well [10]. A summary of Mexico's main climate change goals is presented in table 1. If Mexico meets all the milestones set by these policies, it will be in line with the most aggressive mitigation scenarios set by the Intergovernmental Panel on Climate Change's (IPCC's) fifth assessment report (AR5) [14]. Table 1 summarizes the key goals set by Mexico's different climate change policies:

Table 1. Summary of Mexico's Climate Change Policy Goals

Year	Policy	Goal
2020	LGCC	Reduce emissions by 30% compared to BAU
2024	LGCC, ENCC	Generate 35% of electricity with clean technologies
2026	INDC	Peak GHG emissions
2030	INDC	Unconditional – Reduce emissions of GHG by 22% and Black Carbon by 51%. Total reduction of 25% compared to BAU.
		Conditional - Reduce emissions of GHG by 36% and Black Carbon by 70%. Total reduction of 40% compared to BAU.
2034	ENCC	At least 40% of electricity generated comes from Clean technologies
2050	LGCC	Reduce emissions by 50% compared to 2000
	ENCC	At least 50% of electricity generation comes from clean energies

LGCC - General Law on Climate Change

ENCC - National Climate Changes Strategy

INDC - Intended Nationally Determined Contributions

1.2.3 Integrated Assessment Models (IAM's)

In this dissertation, we are building on the results produced by J. Veysey et al, "Pathways to Mexico's Climate Change Mitigation Targets: A Multi-Model Analysis" [3]. This paper used a series of IAMs to study the development of Mexico considering the country's climate change goals.

IAMs are generally used to study policy and climate change under a wide range of scenarios. These models can combine economic, energy, technology and climate models to better understand the interactions of these systems under different policy scenarios. There are two main categories that IAMs can be divided into: bottom-up models that use detailed technological models to simulate the economy and top down models that optimize aggregated representations of the economy [12]. Bottom-up models look for the most cost-effective solution to reach a specific policy from a microeconomics point of view, and top down models look at the effects of policies from a macroeconomic level [13]. Table 2 shows a summary of the characteristics of the IAMs used in this study [3].

Table 2. IAM Characteristics

Model	Institution	Model Type	Regions
EPPA [15]	MIT	Global general equilibrium model	16
GCAM [16]	Pacific Northwest Laboratory, United States	Global energy system and land use model	32
IMAGE [17]	Netherlands Environmental Assessment Agency, The Netherlands	Global energy model with sub model for land use	26
Phoenix [18]	Penn State University	Global general equilibrium model	26
Poles [19]	ENERDATA, UK	Energy market equilibrium model	50
TIAM-ECN	Energy Research Center of the Netherlands	Global bottom-up linear optimization energy system model	20

1.3 PEGyT Model

The Planning of Expansion of Generation and Transmission (PEGyT) model was developed by the Institute of Electricity and Clean Energy (INEEL) in Cuernavaca Mexico in 1993. From its development, it has been used in many studies in the development of the Mexican electrical gird. The PEGyT model determines a minimum investment and operating cost expansion plan for the generation and transmission expansion problem within the electrical grid in Mexico. The model creates each multi-year expansion plan to meet the energy demand at each specified time-period in the most economical way possible within the technical constraints defined in the model. The PEGyT model is a linear programming model run through CPLEX [2].

Within the PEGyT model the Mexican electrical grid is composed of 47 nodes, 9 areas of operation and 64 connections. These can be seen in the following Figure 2 and Table 3.

Definition of the components of the model:

- Nodes – Represent the main points for the electrical grid which can represent a load center, a point of generation or both. Nodes have specific geographical information attached such as what generation technologies can be deployed there, altitude and additional costs in transportation of fuel or investment associated with the region.
- Connections – Define the existing and possible links for the transmission of electricity in between nodes.
- Areas of Operation – Groups of nodes that share common behavior in demand and demand growth.

Table 3. Areas of Operation and Nodes

Area of Operation	Node Name	Number	Area of Operation	Node Name	Number
North East	Monterrey	16	**West**	San Luis Potosi	24
	Rio Escondido	12		Queretaro	29
	Saltillo	17		Salamanca	25
	Nuevo Laredo	13		Aguascalientes	23
	Reynosa	14		Guadalajara	22
	Matamoros	15		Manzanillo	26
	Huasteca	19		Tepic	21
	Cd. Valles	18		Carapan	27
	Tamazunchale	20		Lazaro Cardenas	28
North West	Cananea	2	**Eastern**	Puebla	33
	Hermosillo	1		Poza Rica	31
	Cd. Obregon	3		Veracruz	32
	Los Mochis	4		Coatzacoalcos	36
	Mazatlan	6		Tabasco	37
	Culiacan	5		Grijalva	38
North	Chihuahua	9		Temascal	35
	Durango	10		Acapulco	34
	Cd. Juarez	7	**Peninsula**	Lerma	39
	Laguna	11		Merida	40
	Mocezuma	8		Cancun	41
Baja California	Ensenada	44		Chetumal	42
	Mexicali	45	**Central**	Central	30
	Tijuana	43			
	San Luis Rio Colorado	46	**Baja California Sur**	La Paz	47

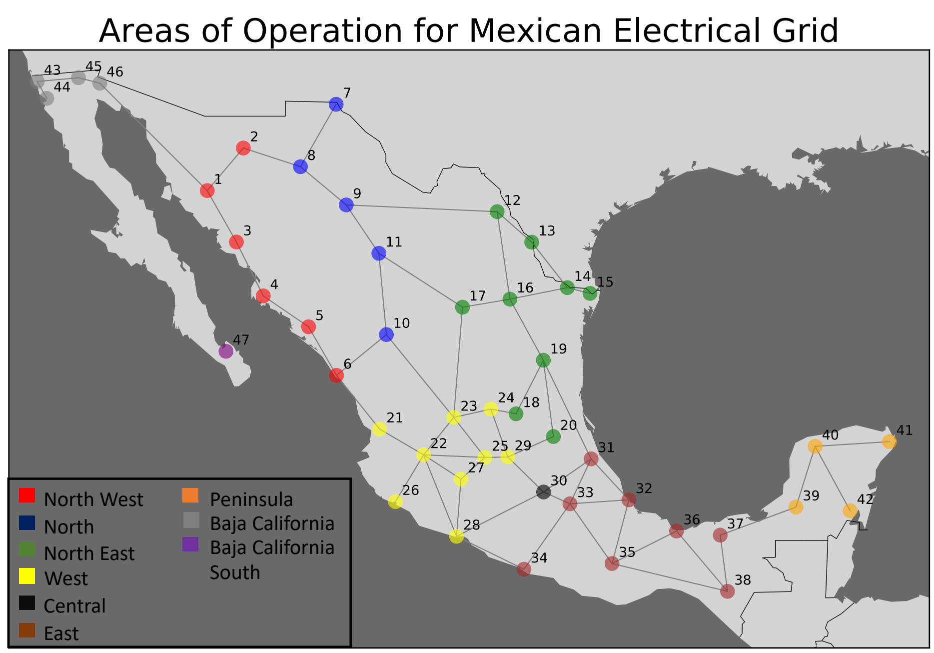


Figure 2. Areas of Operation for the Mexican Electrical Grid in PEGyT Model
Small numbers at each node indicate demand or production points within the system, color indicates area of operation

The PEGyT model has been set up to create an expansion plan for the Mexican electrical grid from 2016-2050 as these are the years considered by Mexico's current climate change goals. This time frame is broken up into 19 periods (2016-2030, 2035, 2040, 2045, 2050). The first group of periods 2016-2029 are expressed annually, one period is equivalent to one year, as these are the time-period where we have the most information on already planned expansions to generation and transmission [5]. The last group of periods 2030, 2035, 2040, 2045 represent 5 years per period (2030-2034), this is done to save computational time on each simulation. For each of these time periods defined in the PEGyT model it will consider 3 seasons per year to account for the seasonal variation in demand as well as hydrological resources.

The PEGyT model obtains an optimal expansion plan after iterating back and forth from the first to the last planning period until the tolerance criteria is met. At each time step the PEGyT model is broken up into a main and subproblem that have to be solved separately. First the PEGyT model will solve the main problem at period t in which it decides on how much installed generation and transmission capacity will be required for that period. This expansion information is then passed on to the production subproblem for period t where the model decides how much electricity the different plants will generate to create an economically optimal production plan. If the existing installed capacity is not enough to meet the demand in the electrical grid, then the main problem will rerun and add more generation capacity to the system. If the existing generation and transmission is enough and an optimal production plan is found for period t then the PEGyT model moves on to the next time period in the expansion plan. This process is illustrated in Figure 3.

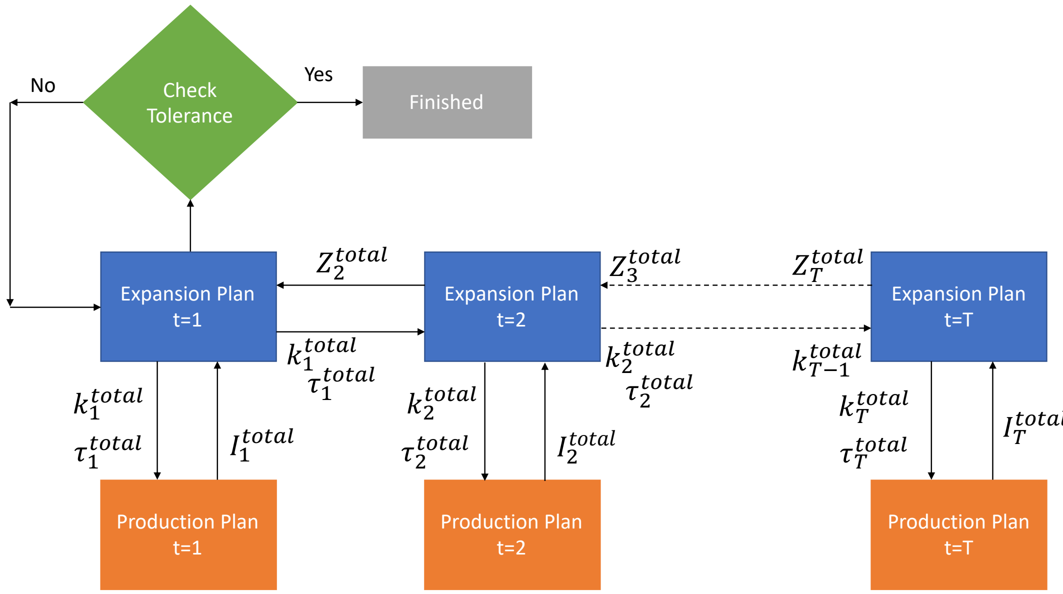


Figure 3. Flow of Information in PEGyT

Where the variables can be defined as:

k_t^{total}- the total amount of generation capacity added for period *t*.

τ_t^{total}- the total amount of transmission capacity added for period *t*.

I_t^{total} – the total cost of the production plan for period *t*.

Z_t^{total}- the total future costs in investments and production for period *t*.

For each time-period the main problem in the PEGyT model will make decisions on:

- How much installed generation capacity should be added to the system and at which nodes?

- k_{ngti} installed capacity at node n of generation technology g at period t in expansion plan i

- What connections require additional transmission capacity?
  - τ_{mti} transmission capacity of link m at year t in expansion plan i

Once the expansion plan is defined the model will make decisions on the production subproblem for each period in the expansion plan:

- How much electricity will be produced by each plant at each node?
- How much power will flow along each transmission line?

The key cost variables, defined by the user, that the model uses to determine an optimal expansion and production plan:

- Overnight and operation and maintenance costs for each generation technology.
- Fuel and water costs.
- Cost of externalities.
- Expected evolution of generation technology and fuel costs.
- Life cycle of generation and transmission infrastructure.
- Discount rate d.

1.3.1 Objective function

The PEGyT model uses a cost minimization objective function. This objective function minimizes the present value of the sum of costs in generation and transmission investments as well as costs of fuel, operation and maintenance, water use and energy not met. This is shown in equation (1):

$$\text{Min} \sum_{t=1}^{T} I_t^{Capacity} + I_t^{Prouction} + I_t^{Transmission} + I_t^{Penalties} \qquad (1)$$

Where $I_t^{Capacity}$ represents the required investment in installed generation capacity at period t, $I_t^{Production}$ represents the required investment in the production plan at period t, $I_t^{Transmission}$ represents the required investment in transmission capacity at period t and $I_t^{Penalties}$ represents the cost of penalties at period t. The PEGyT model will impose economic penalties on the expansion plan for energy not met or clean energy not met as well.

1.3.2 Main Constraints

This section describes some of the most critical constraints in the PEGyT model for our study. The PEGyT model will ensure that all of these constraints are met when developing an expansion plan for each of the IAMs. The variables used to define the main constraints in the PEGyT model are presented in Table 4.

Table 4. Variables in the Main PEGyT Constraints

Variable	Description	Units
$\boldsymbol{y_{ngti}}$	Number of power plants at node n of technology g at period t for expansion plan i	NA
$\boldsymbol{k_{ngti}}$	Installed generation capacity at node n of technology g at period t for expansion plan i	MW
$\boldsymbol{P_{mti}}$	Power flow over line m in period t for expansion plan i	MW
$\boldsymbol{\tau_{mti}^{Cap}}$	Transmission capacity of line m in period t for expansion plan i	MW
$\boldsymbol{CF_{gi}^{min}}$	Minimum capacity factor for technology g for expansion plan i	NA
$\boldsymbol{\varepsilon_{ngti}}$	Energy produced at node n of technology g at period t for expansion plan i	GWh

- Each node n has an upper limit on the number of generation plants per technology g that can be installed period t in expansion plan i.

$$y_{ngti} \leq y_{ngti}^{max} \qquad (2)$$

- The electrical grid can have a minimum required installed generation capacity per technology per period defined within the system.

$$k_{ngti} \geq k_{ngti}^{min} \qquad (3)$$

- Flow conservation has to be maintained at each node for each period. The summation of power flow in and out of a node plus the electricity production and demand at this node must be equal to zero.

$$P_{mti}^{in} + \boldsymbol{\varepsilon}_{ngti}^{Prod} + P_{mti}^{out} + \boldsymbol{\varepsilon}_{ngti}^{Dem} = 0 \quad (4)$$

- The power flow over each transmission line at period t has to be less than or equal to the current capacity of the line m in period t in expansion plan i.

$$P_{mti} \geq \tau_{mti}^{Cap} \qquad (5)$$

- The capacity factor for each generation plant has to be equal to or greater than the minimum load for technology g in expansion plan i.

$$CF_{gi} \geq CF_{gi}^{min} \quad (6)$$

1.3.3 Data - Mexico's Electrical Infrastructure 2016

For this study the PEGyT model is set up and run with the information for generation, transmission and demand for 2016 in Mexico's Electrical grid. This information was compiled from annual reports created by the Secretary of Energy (SENER) and is reviewed in detail bellow.

1.3.3.1 Generation

As of 2016 Mexico has 62,277 MW of installed generation capacity within its electrical grid. Currently the dominating technology is natural gas, with 32,786 MW, 53% of the total capacity. Mexico has 74% of its generation coming from fossil fuels and only 26% from clean technologies, the largest of these being hydro 18% and wind 5% as shown in Figure 4 [4][5]. The geographic distribution of this generation within the Mexican Electrical Grid can be seen in Figures 5 and 6:

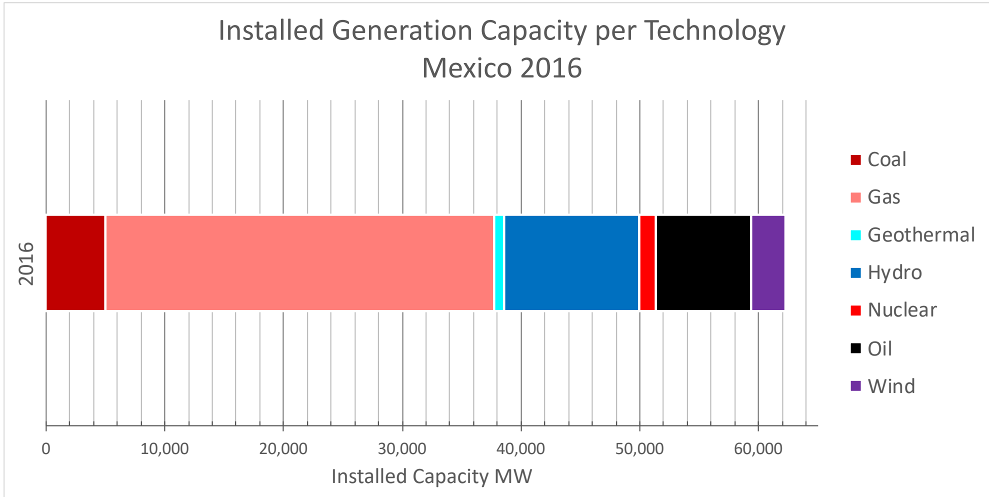


Figure 4. Installed Generation Capacity per Technology in Mexico 2016

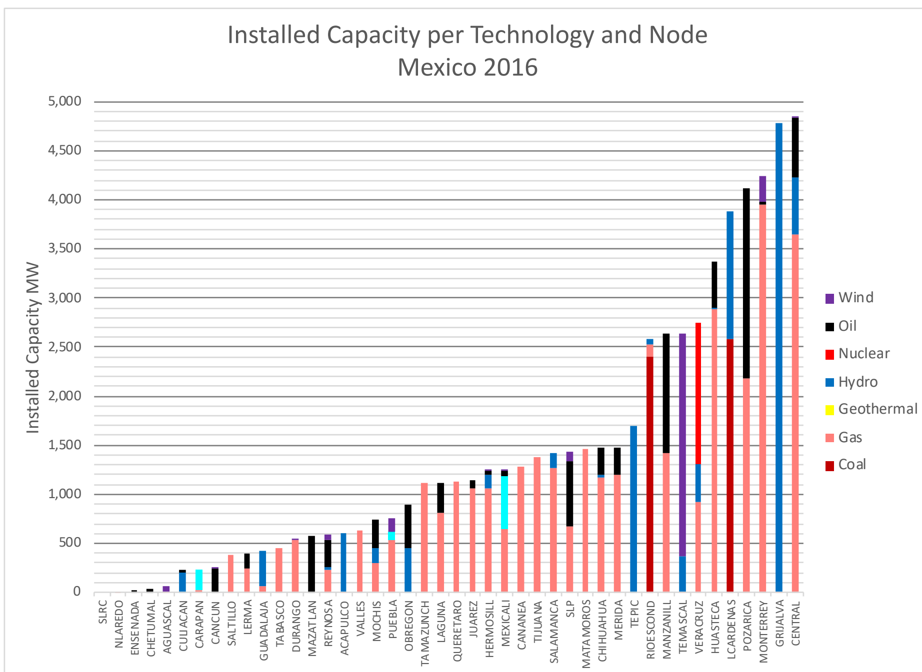


Figure 5. Installed Capacity per Technology and Node Mexico 2016

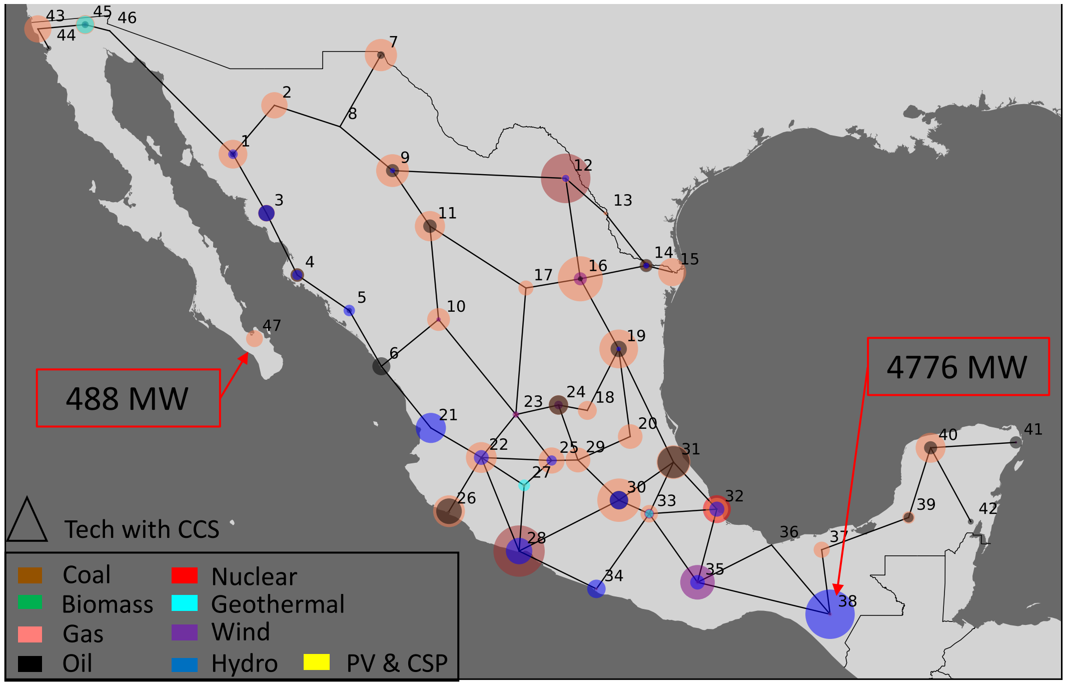


Figure 6. Map of Installed Generation per Technology and Node Mexico 2016
Small numbers at each node indicate demand or production points within the system, size of node represents amount of installed capacity, color indicates technology.

1.3.3.2 Transmission

The PEGyT model considers a simplified representation of the Mexican transmission system in 2016 with 64 connections. Each of these connections contains information on the maximum transmission capacity as well as electrical characteristics such as resistance and impedance. As of 2016 the Transmission system in Mexico has 53,216 km of installed lines and 72,855 MW of transmission capacity, as shown in Figure 7 [5]:

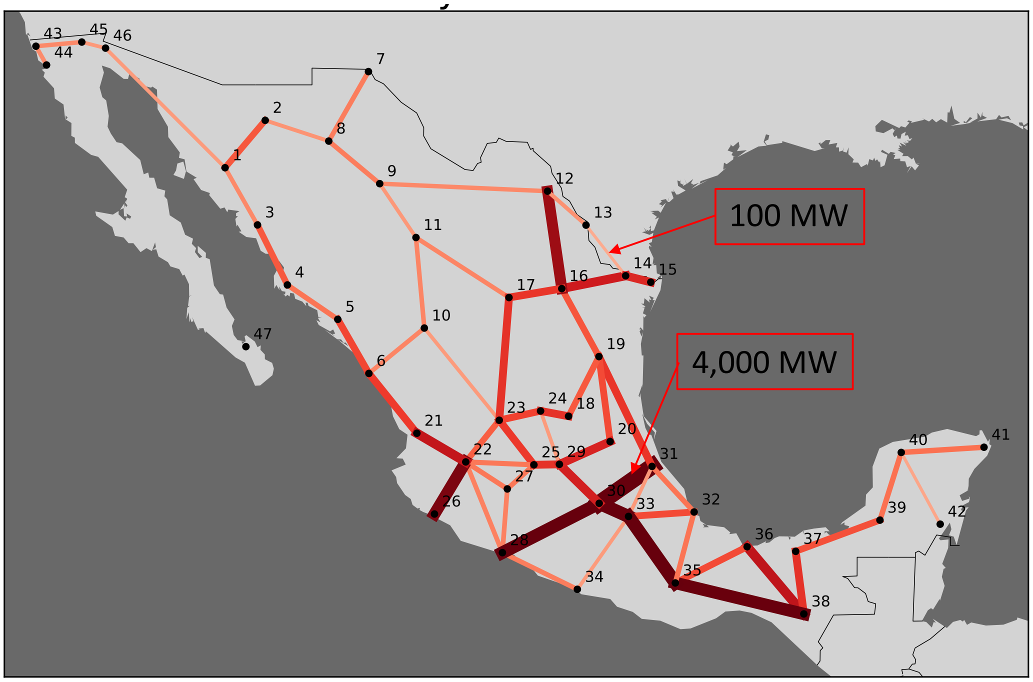


Figure 7. Transmission System Mexico 2016
Small numbers at each node indicate demand or production points within the system. The thickness of the red lines indicates the capacity of each connection. Red boxes indicate amount of transmission capacity for each line.

For the transmission expansion problem, the PEGyT model will choose between 4 options: 230 or 400kv lines in either simple or double circuit. Each of these line configurations will have unique impedance and resistance characteristics. The lines will also have fixed and variable costs. The fixed costs are associated with the infrastructure required at the extremes of each connection such as substations, while the variable costs are related to the length of each line, price of terrain, necessary soil studies, material, transportation and labor among other factors.

CHAPTER 2

ESSAY 1: ROBUST REGIONAL POWER PLANNING TO MEET CLIMATE GOALS (A CASE STUDY ON MEXICO USING IAMS AND PEGYT)

2.1 Abstract

As Mexico and other countries set emission goals due to growing concern about climate change, many questions remain on how these goals can be reached. Is there one development pathway or several and how can we differentiate among them? Previous studies have used a top-down approach with Integrated Assessment Models (IAM) to study possible development pathways. These studies, however, are at very coarse time-steps; and do not include information on the geographic distribution of resources or infrastructure. Moreover, the use of multiple IAMs, while useful, leaves questions as to how policy-makers and planners can use the divergent results. For this study, we use a multi-model approach, implementing each of the IAM pathways in a bottom-up model of the Mexican electrical system, called the PEGyT model. After using a wide range of possible future scenarios provided by seven different IAMs we analyze the results to find critical areas of investment that are robust across scenarios. We find that more diverse energy portfolios require relatively less transmission investment; and that despite a lack of robustness in the location of installed capacity investments, investment in transmission expansions is fairly robust across pathways.

2.2 Motivation

Many countries have set climate goals, particularly within the Paris Agreement where they established their Intended Nationally Determined Contributions (INDC) for the year 2030 [10,59]. One widely employed method to help governments plan for reaching these climate goals is the use of Integrated Assessment Models (IAMs) [3, 60-63]. IAMs combine economic, energy, technology and climate models to better understand the interactions of these systems under various policy scenarios. Since each IAM comes with a specific set of assumptions and structures, it is common to use multi-model studies to account for the uncertainty resulting from different formulations and data sets [64]. Countries, however, are faced with two key challenges in translating the results from multi-model IAM studies into near-term actions. First, these global IAM models have coarse geographic and temporal scales. Individual countries are represented as a single region, or in some cases, grouped together with multiple countries to make up a single region. In addition, the models solve in 5 or 10 year time steps, whereas electricity needs to balance supply and demand every hour of every year. Because of these limitations, previous studies have recognized the need to complement IAM analysis with additional insight from more detailed models to bridge the analytical approach [65, 66]. Second, while using multiple models is crucial given the deep uncertainties around climate change and the economy, it is not clear how policy makers, regulators and planners can make use of widely disparate results.

We address these two challenges, using Mexico's electricity system and climate goals as a case study. We take the study by Versey et al. [3] as a starting point. This study reports on the results of seven IAMs, each finding a cost-effective path to the goal of reducing emissions by 50% in 2050 compared to 2000 emissions, as set out in the National Climate Change Strategy Report [1]. Each IAM provides a path, detailing the mix of energy generation from different technologies to reach Mexico's 2050 climate change goals. The 2050 energy generation portfolios are presented in Figure 8.

For each IAM energy portfolio we create a detailed expansion plan, which refers to all the relevant expansions to transmission and generation, as well as a production plan, which states where and when electricity is being produced. This information is critical in identifying the feasibility of different IAM energy portfolios as well as the impacts on transmission infrastructure within the Mexican electrical grid. Using this information, we can identify robust strategies for development and near-term decision making. The expansion plans for all IAM scenarios will be presented in section 2.6.

2.3 Research Question

We have two main questions in this essay. First, what are the geographic impacts of various expansion plans on the electricity grid? Second, what are near term robust strategies for meeting these goals? We use a multi-model approach to study a series of pathways created by IAM's (top-down approach). Each IAM proposes a portfolio that would help Mexico reach its climate change goals in 2050 and create an expansion plan for them using a detailed model of the Mexican electrical grid (bottom up approach with the PEGyT model).

2.4 Methodology

To create an expansion plan for each of the IAM portfolios within the PEGyT model we need to define an installed generation capacity portfolio capable of recreating the electricity portfolio presented in Figure 8. Thus, here we describe how we translate the energy portfolio provided by the IAM into an installed capacity portfolio. This iterative methodology for the PEGyT model is further illustrated in Figure 9, and Table 5 shows the user defined variables required in this process.

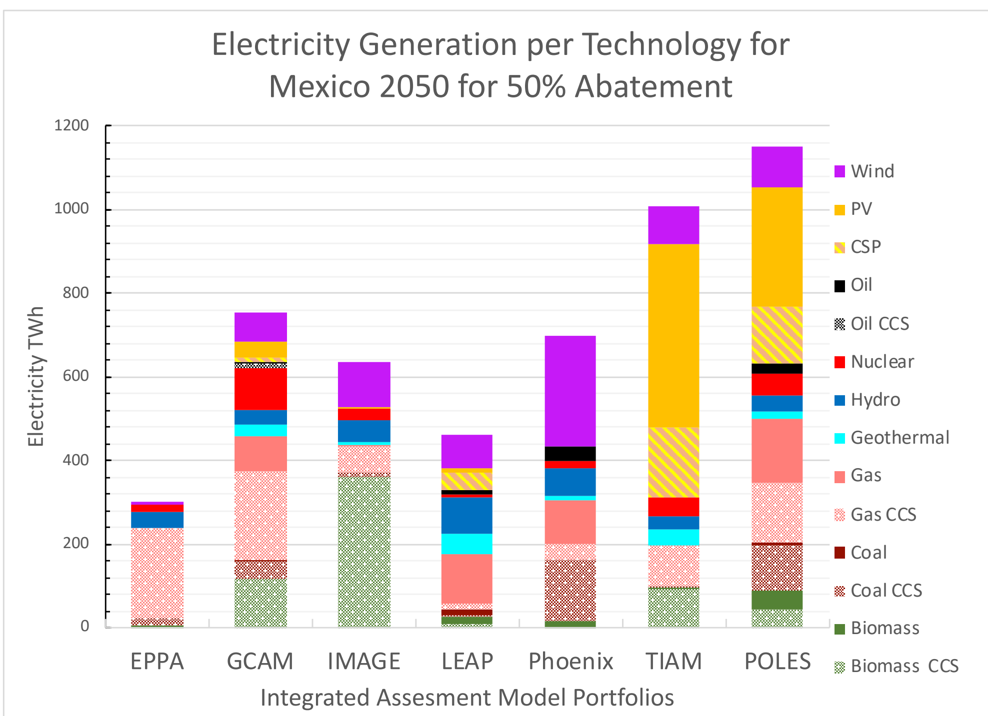


Figure 8. Electricity Generation per Technology for Mexico 2050 for 50% Abatement

Table 5. Variables used in Methodology

Variable	Description	Units
y_{ntgi}^{max}	Number of power plants at node n of technology g at period t for expansion plan i	Power Plants
k_{tgi}^{min}	Installed generation capacity of technology g at period t for expansion plan i	MW
CF_{gi}^{min}	Minimum capacity factor for technology g for expansion plan i	Unitless
ε_{ngti}	Energy produced at node n of technology g at period t for expansion plan i	GWh

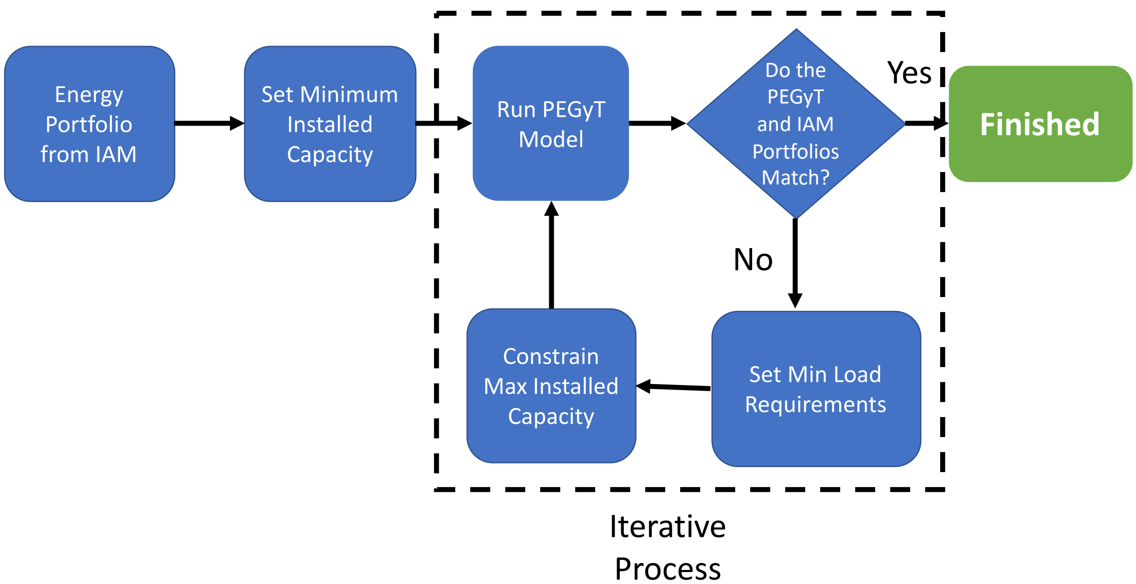


Figure 9. Methodology for Creating IAM Expansion Plan in PEGyT

For each IAM expansion plan, we follow an iterative process, as follows:

- The first step is to estimate the minimum installed generation capacity k_{tgi}^{min} required for technology g, in planning period t and expansion plan i, to produce the desired levels of energy. We will use this value to set a constraint within PEGyT for each period defining the minimum installed capacity for each technology g. We accomplish this step by using the maximum operating capacity factor (CF) for each technology to translate energy into installed capacity, as shown in equation (7):

$$\frac{\varepsilon_{tgi}}{CF_g * 8760} = k_{tgi}^{min} \qquad (7)$$

Where:

ε_{tgi}- energy produced at period t by generation technology g in expansion plan i

CF_g- capacity factor for generation technology g

8760 – hours in one year

However, as the PEGyT model optimizes the production plan for electricity for min cost considering the available generation capacity, some plants may not operate at their maximum CF. The next two steps are intended to get the model to produce the correct amount of energy. At this point, we run PEGyT and compare the resulting energy portfolio in 2050 with those produced by the IAM.

- If the PEGyT energy portfolio in 2050 does not match the IAM energy portfolio, we define a minimum operating capacity factor CF_{gi}^{min} for technology g and expansion plan i. This will ensure that the installed generation capacity is operating at the desired levels. This is required because the first step, setting a constraint on k_{ntgi}^{min}, will ensure the desired amount of generation capacity is installed per technology; but the production plan may decide to use a less expensive technology to produce the required electricity to meet the demand.

After setting CF_{gi}^{min} for the desired generation technologies we run the PEGyT model again to test the 2050 energy portfolio.

- If the PEGyT energy portfolio in 2050 still does not match the IAM energy portfolio, we set an upper limit to the number of power plants y_{ntgi}^{max} that can be installed for node n, technology g, planning period t and expansion plan $\boldsymbol{i}$. This will prevent the PEGyT model from installing an excess amount of generation capacity of a given technology that may produce more than the desired amount of electricity.

In the following sections we provide the necessary information to set up the PEGyT model to create the different expansion plans. Section 2.4.1 provides an overview on the different projections on electricity demand among the IAM, section 2.4.2 explains how the electricity demand is defined for each IAM expansion plan in the PEGyT model, and section 2.4.3 defines the starting conditions for the PEGyT model.

2.4.1 Electricity Demand

In this section we discuss our assumptions on electricity demand for each IAM portfolio, and how the electricity demand is defined in the PEGyT model. Each IAM portfolio has a unique projection on electricity demand up to the year 2050, as shown in Figure 10, resulting from differences in assumptions on economic growth and energy efficiency measures. Each of the IAMs has its own definitions for overnight costs, electricity demand, renewable resource availability, technology availability, constraints on production and the rate at which technologies can integrate to the grid.

A key assumption in this paper is that the differences in overall electricity demand *do not reflect differences in access to electricity or quality of life*. We assume that the differences reflect different assumptions within each IAM on energy policy, electrification and economic growth. For example, EPPA has the smallest projected demand in 2050 due to assumptions made on high levels of energy efficiency. GCAM, Phoenix and TIAM predict higher electricity demand by 2050 compared to the other IAMs, due to assumptions on the electrification of other sectors such as transportation. A more detailed analysis of the factors influencing the different projected electricity demands for each IAM can be found in J. Veysey et al, [3].

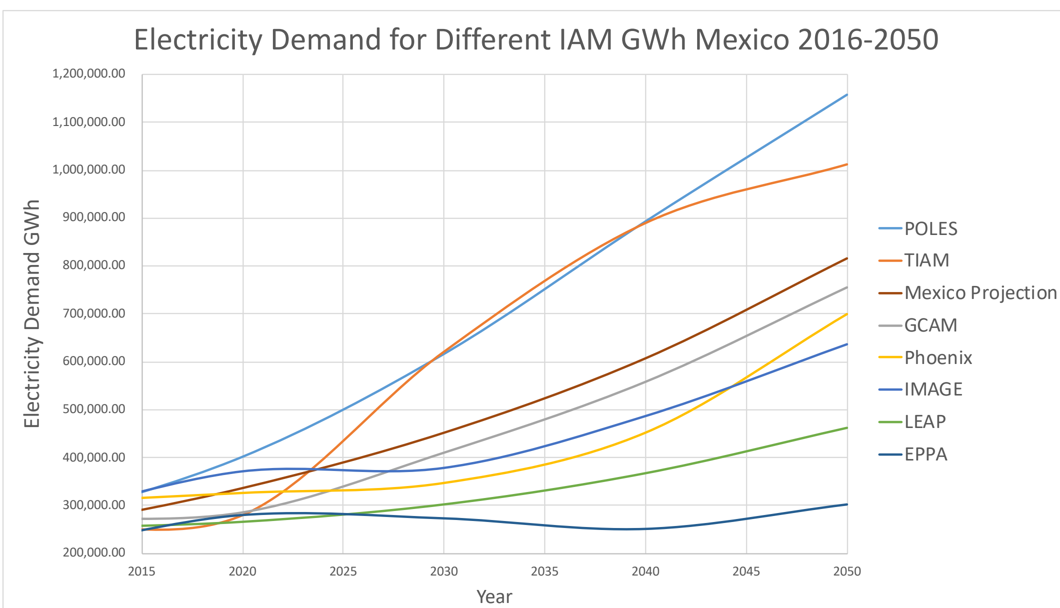


Figure 10. Electricity Demand per IAM, GWh Mexico 2016-2050

Figure 10 includes the projected average annual electricity demand growth rate by the Mexican government of 2.9% for 2016-2030 [5]. We have extended this growth rate up to 2050. Figure 10 shows that the projections from the Mexican government for future electricity demand are high compared to most of the IAM predictions with only TIAM and POLES predicting higher demand overall.

2.4.2 Energy Demand in the PEGyT Model

The growth in electricity demand in the PEGyT model for each period is defined by the user for each expansion plan. It is possible to set different growth rates for the different areas of operation of the Mexican electrical system within PEGyT, but for simplicity in this study we will assume the same growth rate for all areas of operation. The PEGyT model constructs a load duration curve for each period within the studied time frame (2016-2050). To construct the load duration curve, the model requires the user to define the two following variables for each period to completely describe behavior of the electricity demand for any expansion plan:

- Final Demand per period (GWh)- The total amount of electricity consumed by end users in the system.
- Peak Demand per period (MWh/h)- This is the maximum peak in demand that must be met for any given planning period.

Regardless of the IAM portfolio we are evaluating, we use the same initial conditions that reflect the state of the Mexican electrical grid in 2016. A total of 298,792 GWh of electrical energy was consumed with a peak demand of 40,893

MWh/h and a minimum demand of 18,723 MWh/h. Detailed information per operating area is provided in Table 6 [8].

We obtained the electricity demand for each IAM across the planning period 2016-2050 from the online database at [42]. This database provides the electricity demand for Mexico at 10-year intervals 2010, 2020 and up to 2100. As mentioned previously in the background section 1.3 the PEGyT model is run for every year from 2016 to 2030 then run at 5-year intervals up to 2050. Because the IAM do not provide electricity demand information at the same resolution as the PEGyT model, we calculated an average demand growth rate for each IAM in each period. These annual growth rates are applied to the initial 2016 values of final and peak demand to calculate future demand values for all the required periods in the PEGyT model. This allows the PEGyT model to recreate the different IAM demand projections within the Mexican electrical grid. The tables with the PEGyT inputs for final demand and peak demand for the different IAM scenarios can be found in Appendix 6.1.

Table 6. Demand Consumption data for 2016

Area	Peak Demand MWh/h	Final Demand GWh	Average Growth Rate % 2017-2031	
			Final Demand	Peak Demand
Central	8,567	59,103	2.0	2.1
Northeast	8,710	52,297	3.1	3.1
Northwest	4,350	23,389	3.3	3.2
North	4,258	24,696	3.0	2.9
West	9,351	63,407	3.3	3.2
East	7,128	47,642	2.8	2.7
Peninsula	1,893	12,129	3.8	3.8
Baja California	2,621	13,438	2.8	2.8
Southern Baja California	470	2,692	3.9	4.0

2.4.3 PEGyT Set up

The PEGyT model allows us to take the electricity portfolios from [3] shown in Figure 8 and obtain detailed information on how the electrical system will have to be developed. For all the IAM portfolio, we start with the same initial conditions by defining the current state of the Mexican electrical grid, in 2016, in terms of installed capacity and transmission, as shown in Figure 11 [4]. After setting the initial conditions we create the optimal expansion plan for each scenario, using the methodology previously explained.

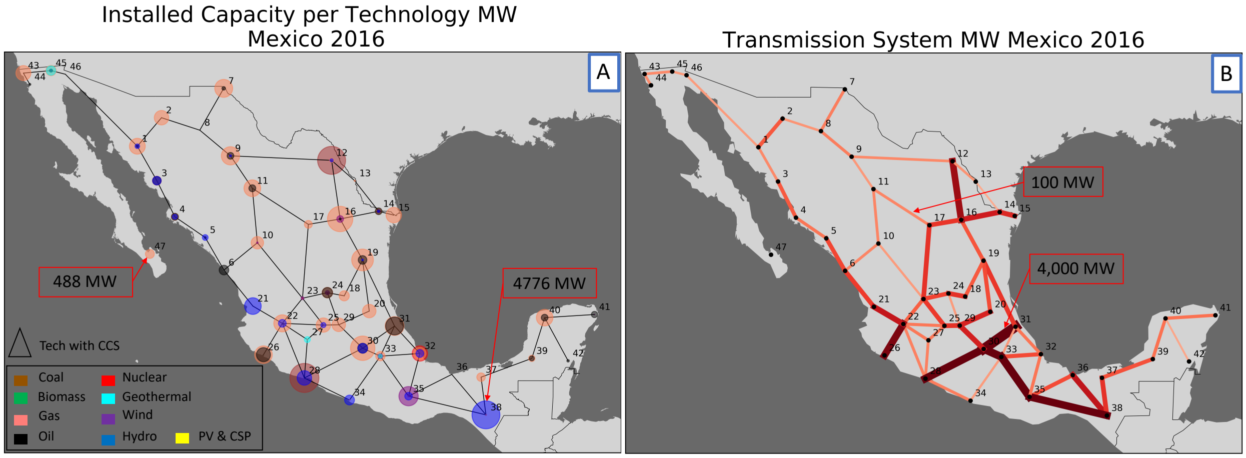


Figure 11. Initial Conditions for Mexican Electrical Grid in 2016
Small numbers at each node indicate demand or production points within the system, size of node represents amount of installed capacity, color indicates technology. The thickness of the red lines indicates the capacity of each connection. Red boxes indicate amount of installed capacity at node or transmission line.

2.4.4 PEGyT Outputs

For each expansion plan that the PEGyT model creates it will produce the outputs shown in Table 7. These outputs will be analyzed and represented geographically in the results section 2.6 to provide insight for better electricity planning.

Table 7. PEGyT Model Outputs

Variable	Description	Unit
k_{tngi}	Installed generation capacity added in period t at node n of technology g for expansion plan i.	MW
ε_{tngi}	Electricity produced in period t at node n by technology g for expansion plan i.	GWh
e_{tngi}	CO_2 emissions produced in period t at node n by technology g for expansion plan i.	Mton
ζ_{tnfi}	Fuel used in period t at node n of fuel type f for expansion plan i.	MCAL
τ_{mti}	Transmission capacity of line m in period t for expansion plan i.	MW
I_{ti}^{Gen}	Total overnight costs for new installed generation for period t and expansion plan i.	2016 USD
I_{ti}^{Tran}	Total overnight costs for new installed transmission capacity for period t and expansion plan i.	2016 USD
I_{ti}^{Prod}	Cost of production plan to produce the required level of electricity for period t and expansion plan i. Includes fuel costs and fixed and variable O&M costs.	2016 USD

2.5 Data

2.5.1 Generation Technology Description and Future Projections

To recreate the scenarios established in (Veysey, 2015) [3] we model a variety of conventional and clean generation technologies. For each generation technology we defined their three main economic characteristics: Overnight Capital costs which represent the costs incurred in the installation of a new power plant; Fixed Operation and Maintenance represent the costs that a given plant will incur each year independent of how much electricity it produces; and Variable Operation and Maintenance costs are proportional to the amount of electricity produced. This information was obtained from NREL reports [6] and the summary of the overnight costs, O&M fixed and variable can be seen in Table 8:

Table 8. Economic Characteristics of Generation Technologies

Technology	Overnight Capital Costs Million $/MW	Fixed O&M $10,000 MW-yr	Variable O&M $/MWh
Wind	1.73	51.27	0.00
PV	1.98	17.00	0.00
CSP	8.02	66.00	4.00
Geothermal	5.02	155.00	0.00
Natural Gas	1.02	14.48	3.49
Natural Gas CCS	2.12	32.27	6.89
Coal	3.79	52.19	7.34
Coal CCS	6.54	73.96	8.58
Oil*	3.79	52.19	7.34
Oil CCS*	6.54	72.96	8.54
Nuclear	5.49	94.72	2.17
Biomass	3.72	107.26	5.34
Biomass CCS**	7.07	195.50	8.39

* Oil and Oil CCS costs are modeled the same as coal.
** Biomass CCS cost are estimated based on cost change in coal and natural gas with and without CCS.

The PEGyT model also takes into account forecasts on how the costs of different generation technologies will evolve over the established time frame of 2016-2050, as shown in Figures 12 and 13 [6]. Variable O&M costs are assumed to stay constant throughout the established time horizon of 2016-2050.

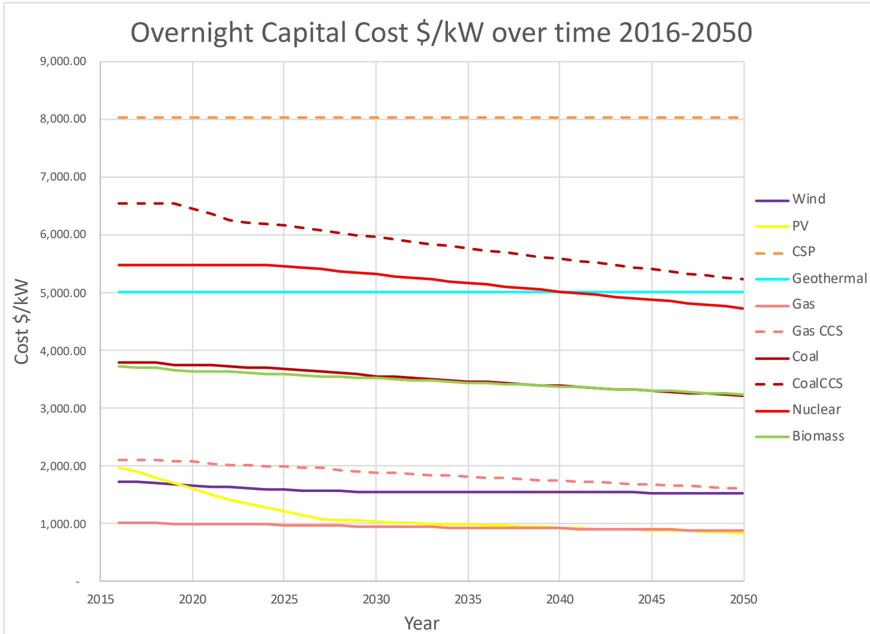


Figure 12. Overnight Capital Costs $/kw 2016-2050

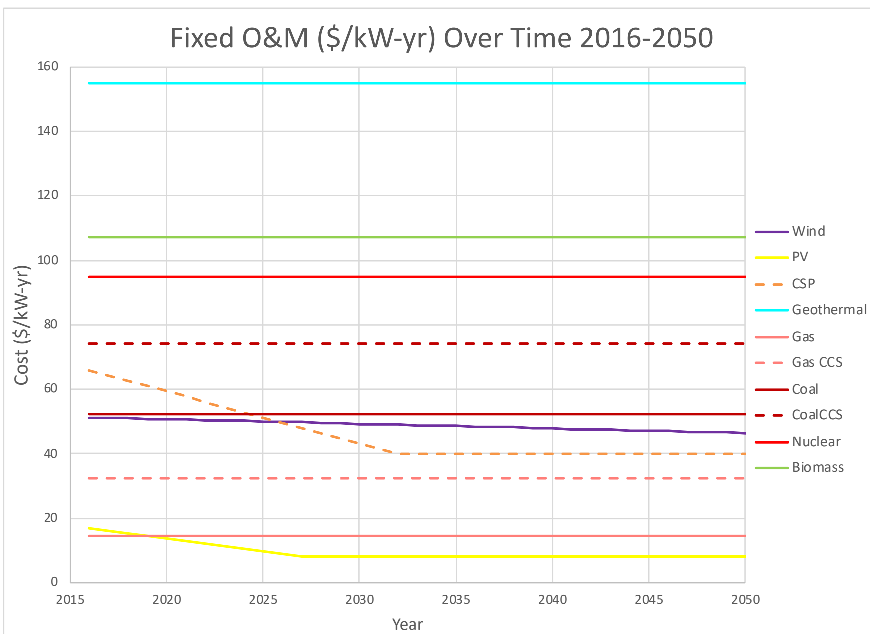


Figure 13. Fixed Operation and Maintenance Costs $/kW-yr 2016-2050

Restrictions of Generation Distribution

2.6 Results

For each IAM electricity portfolio in Figure 8, we present the required installed generation capacity portfolio, as well as additional transmission capacity in terms of power multiplied by the km of each line expansion in Figure 14. The installed generation capacity represents the minimum required capacity to reproduce the desired energy portfolio for each IAM, as explained in the methodology section, and the added transmission capacity reflects the required expansions necessary to ensure all nodes meet their electricity demand.

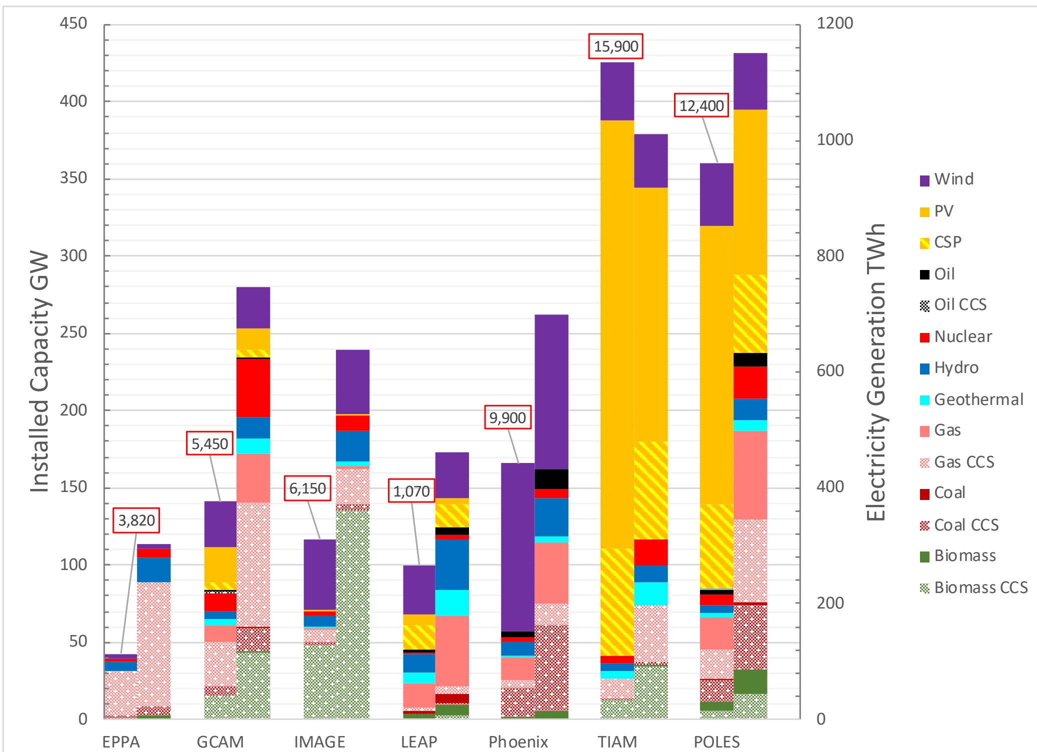


Figure 14. Electricity Generation, Installed Capacity and Transmission added by Scenario for Mexico 2050 50% Abatement

Left bar indicates installed capacity in each IAM scenario and right bar indicates energy produced per technology. The number in a red box above the Installed Capacity of each IAM indicates GW*km of transmission capacity added in each expansion plan.

The information provided in Figure 14 is useful in highlighting the interactions between installed generation capacity, electricity generation and how much transmission capacity is added to the system. In the following section we provide information on how these installed generation portfolios are deployed geographically and what implications that can have on electricity planning.

2.6.1 IAM to PEGyT Results

Figure 15 gives a summary of the expansion plans produced by the PEGyT model for the GCAM and EPPA IAM portfolios within the Mexican electrical grid for 2050.

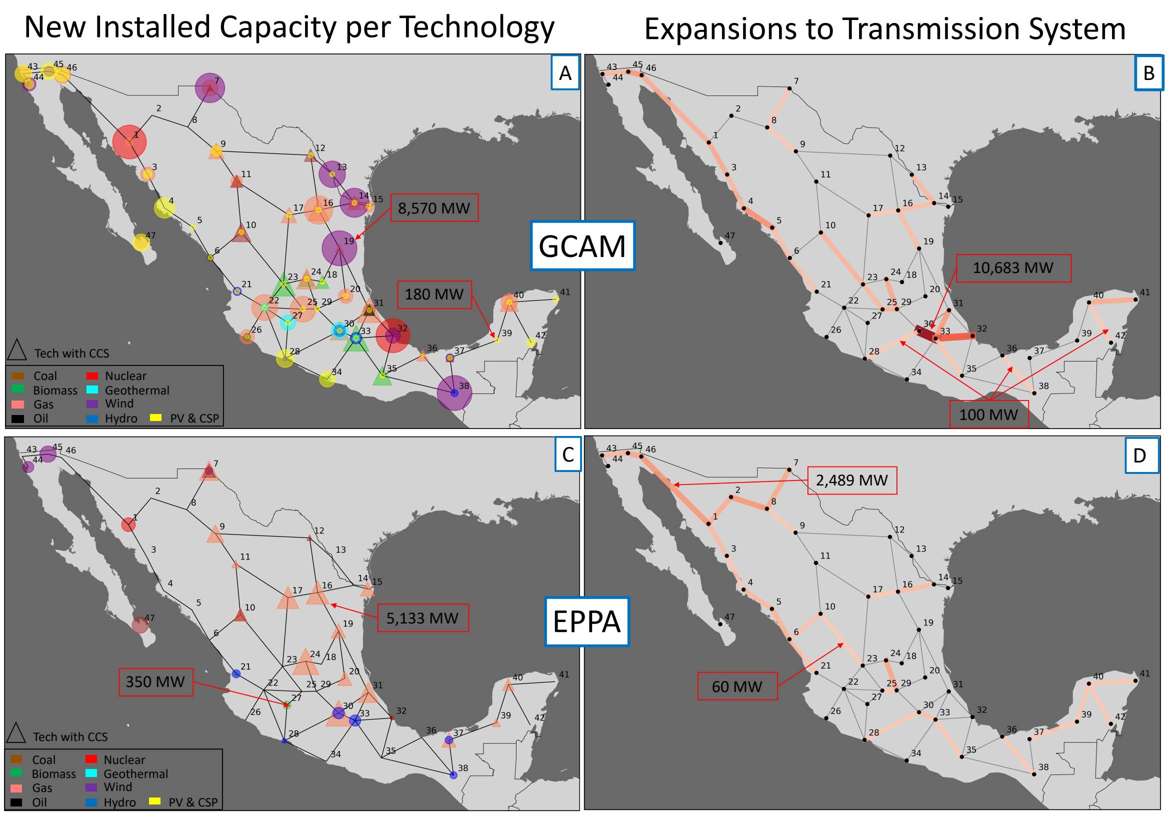


Figure 15. Generation Capacity and Transmission Expansions to the Electrical Grid for GCAM and EPPA 2050

Small numbers at each node indicate demand or production points within the system, size of node represents amount of installed capacity, color indicates technology. Grey transmission lines have not been expanded from 2016-2050 and the thickness of the red lines indicate the amount of expansion to each connection. Red boxes indicate amount of installed capacity at node or transmission line.

Figure 15-A shows that for the GCAM scenario we have a substantial amount of CCS (coal, gas and biomass) deployed within the grid but never along the pacific coast. Because of tectonic and volcanic activities in these regions, CCS technologies have limited viability along the Pacific coast [29, 30]. The largest PV and CSP plants within the grid are present along the pacific coast, in order to compensate for the fact that CCS technologies cannot be deployed in this area. This also helps to reduce the amount of required transmission expansions within the system. Figure 15-B shows the lines with the largest expansions are Central – Puebla (30-33) with 10,683 MW and Puebla – Veracruz (33-32). This reflects the fact that Central (30), which consists of the State of Mexico and Mexico City, represents over 20% of the total load within the national grid. Because this region is also very densely populated, the PEGyT model limits the amount of generation that can be deployed on this node, resulting in the need to import electricity from other nodes.

We also analyze the EPPA scenario Figure 15-C and 15-D as it represents one of the more extreme cases out of the IAMs considered. This is due to EPPAs assumptions on energy efficiency and its limited electricity portfolio with gas-CCS providing 70% of the electricity. In figure 15-C, similarly to the GCAM results, CCS technologies cannot be deployed along the pacific coast. This results in the EPPA expansion plan having minimal installed generation along Mexico's Pacific coast as CCS technologies cannot be deployed in these areas. The only generation present along the pacific coast are a nuclear plant, some wind farms and a coal plant. Due to having minimal generation on the pacific coast the system has to invest in more transmission along the coast to import the necessary electricity as shown in Figure 15-D.

Similarly, the IMAGE electricity portfolio also has significant contributions from CCS technologies with over 50% of the electricity production in 2050 coming from biomass-CCS. Because of this we find similarities in the distribution of installed capacity and transmission expansions between EPPA and IMAGE. The results for the remaining IAM expansion plans are presented in Appendix 6.2. In contrast to EPPA, IMAGE considered a higher electricity demand growth, as shown in Figure 10, which results in the largest transmission expansions along (24-25) to help supply Mexico City (30) with electricity. In general, we find that the more diverse the installed generation capacity portfolio is the more efficient the expansions are in the transmission system, measured in terms of MW*km of additional transmission capacity per MW of installed generation capacity. Here we refer to energy diversity as measured by the Shannon-Wiener index. For a definition of this index refer to Chapter 4 section 4.5.7.

2.6.2 Identifying Robust Areas for Development

In this study we define robust developments as the minimum amount of installed generation capacity at each node within the electricity system across all 7 expansion pathways. We will focus on the following three metrics:

- Minimum Installed Generation (MIG) - the sum of minimum installed generation capacity at each node within the electricity system in 2050.
- Minimum Installed Generation per Technology (MIGT) - the sum of minimum installed generation capacity for each specific technology at each node within the electricity system across in 2050.
- Minimum Installed Transmission (MIT) – the sum of minimum installed transmission capacity to each connection within the electricity system in 2050.

It is important to note that MIG and the sum of MIGT across technologies will not be equal. This is due to the fact that it is possible to have MIG at a node across different expansion plans, but this installed capacity at that node may be composed of different generation technologies across scenarios. This means that a node can have a positive value for MIG but a zero value for MIGT. This results in MIG always being greater than or equal to MIGT in all scenarios. The MIG and MIGT results presented for all scenarios consider the new installed capacity that is added to the system. Because of this MIG and MIGT do not take into account the 11,286 MW of installed hydro capacity and 2,884 MW of installed nuclear capacity present in 2016 that the model assumes will remain operational in the system across the planning period up to 2050. This is an underlying assumption of the model.

We will refer to subsets of 5, 6 or 7 expansion plans as scenarios, which we will use to observe the impacts on MIG and MIGT. This helps to identify any outliers among expansion plans, as there may be an expansion plan that greatly changes the minimum amount of installed capacity within the system. Within these scenarios we are also interested in identifying what are the robust expansions to the transmission system and what lines are always expanded and by how much. Figure 16 summarizes the scenarios with the highest effects on MIGT and MIG. The results are ordered left to right from highest MIG to lowest.

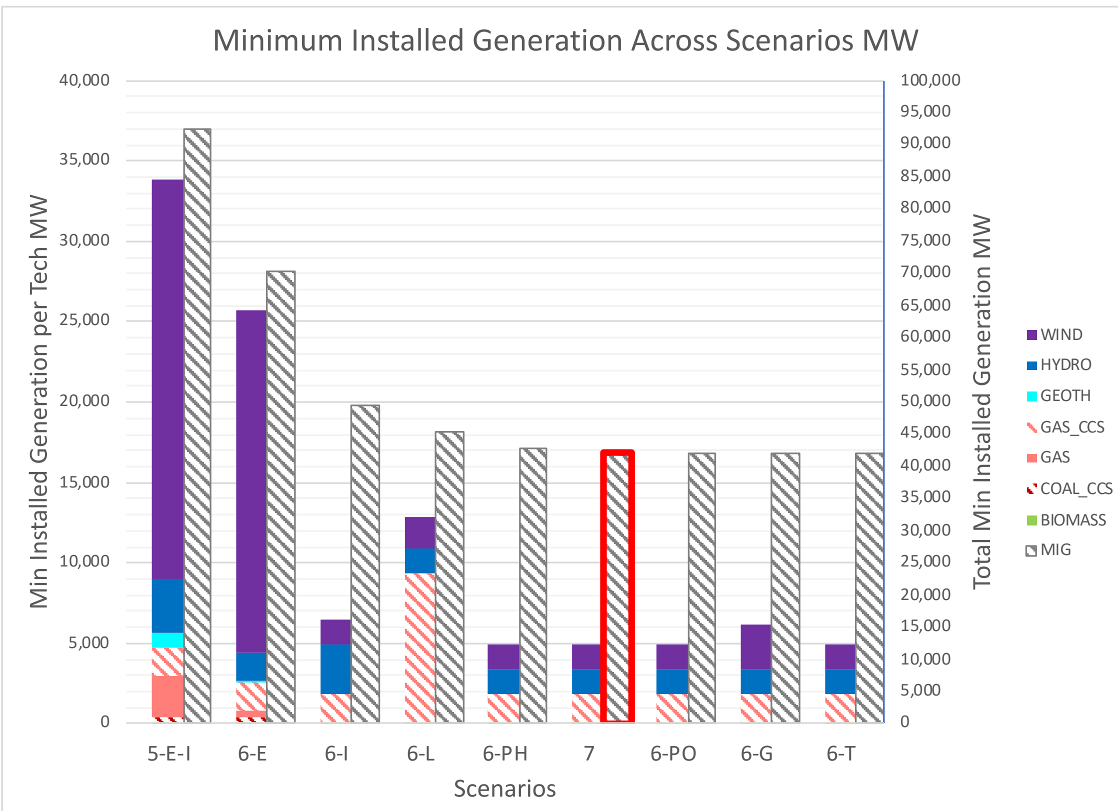


Figure 16. New Minimum Installed Generation Across Scenarios

Each scenario is identified by a number that indicates how many expansion plans are being compared and is followed by a letter indicating what expansion plan is omitted in that scenario. Scenario's 7 MIG is highlighted in red indicating the scenario where all expansion plans are considered

E – EPPA I – IMAGE L- LEAP PH – Phoenix PO – POLES G – GCAM T – TIAM

From Figure 16 we observe that when considering all 7 scenarios, highlighted in red, the most robust technologies to invest in, listed from largest contribution to smallest, are gas with ccs, hydro, wind and small amounts of coal with ccs and biomass. Figure 16 shows that the 2 expansion pathways that have the largest impact on MIG and MIGT are EPPA followed by IMAGE. The omission of any of the other expansion plans has a minimal effect on MIG and MIGT. One of the biggest observable impacts is that without the EPPA results all other scenarios have at least 20,000 MW of wind generation. EPPA has such a strong impact on MIG and MIGT because of the ambitious energy efficiency goals that this IAM assumes for Mexico to be able to reach their 2050 goals. Because of these energy efficiency goals, the electricity demand in Mexico remains almost constant from 2016 to 2050, as shown in figure 10, which greatly reduces the amount of installed capacity that has to be deployed within the electricity system when compared to the other IAMs. Another contributing factor to why EPPA has such a strong effect on MIG and MIGT is because it has the least diverse electricity portfolio by only using 6 generation technologies, 70% of the electricity coming from gas ccs and having the smallest contribution of wind from any expansion plan. IMAGE also has a strong impact on MIG and MIGT due to its reliance on biomass with ccs with 56% of the electricity production in 2050 coming from this technology, while the other expansion plans use minimal amounts of biomass with ccs.

If we analyze the scenario 5-E-I in Figure 16, which has the highest MIG and MIGT out of any scenario, we find that the robust investment in biomass, coal with ccs and gas with ccs does not increase compared to scenario 7. On the other hand, the investment in wind increases dramatically from 1,500 MW to 24,000 MW in scenario 5-E-I. Thus, wind is likely to be a critical component in helping Mexico reach its long-term climate change goals, unless Mexico has aggressive energy saving strategies reflecting EPPA, or heavy investment in biomass-ccs, reflecting IMAGE.

The information provided in Figure 16 can be broken down into MIG and MIGT per node data, as presented in Figure 17. This helps us identify nodes with robust development within the electrical grid that planners can focus their attention on for generation capacity expansion. Having a detailed breakdown of minimum installed generation capacity per technology and node is of value for decision makers in knowing which areas are more likely to develop specific technologies.

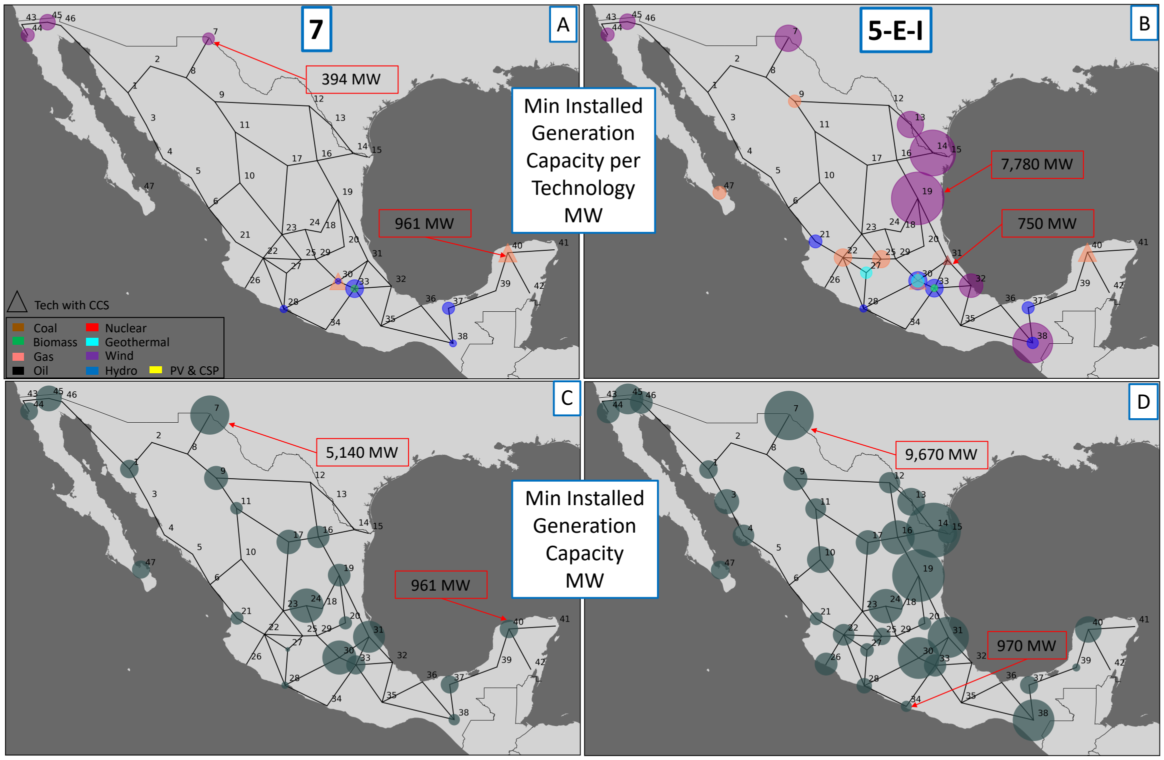


Figure 17. Comparison of MIG and MIGT for scenarios 7 and 5-E-I for Mexico 2050
Small numbers at each node indicate demand or production points within the system, size of node represents amount of installed capacity, color indicates technology. Red boxes indicate amount of installed capacity at node**.**

From figure 17-C we can observe that nodes 7 (Juarez), 14 (Reynosa), 24 (San Luis Potosi), 30 (Central), 31 (Poza Rica) and 40 (Merida) have the highest levels of MIG across all seven scenarios. It is interesting to note that while nodes 7 (Juarez) and 24 (San Luis Potosi) have among the highest level of MIG they have little or no MIGT in figure 17-A. This indicates that while these areas will be critical for developing generation across a wide range of scenarios there is no agreement on what technology has to be deployed there.

Figure 17-B illustrates that the presence of wind across the system greatly increases when ignoring the EPPA and IMAGE scenarios. Wind now has a prominent

presence in nodes 7 (Juarez), 13 (Nuevo Laredo), 14 (Reynosa), 19 (Huasteca), 32 (Veracruz) and 38 (Lerma). Geothermal becomes a robust investment in 27 (Carapan), 30 (Mexico City), 33 (Puebla), coal with ccs in 31 (Poza Rica) and we even have some robust gas investments in nodes 9 (Chihuahua), 22 (Guadalajara), 25 (Salamanca) and 47 (La Paz).

We are also interested in identifying how MIG and MIGT within the system will affect the amount of transmission added to electrical system. For this we also consider the minimum amount of transmission capacity added to each line within the electricity system. This will help us to identify robust connections within the transmission system to reach Mexico's climate change goals. Figure 18 shows MIGT for scenarios 7 and 5-E-I while also showing the minimum amount of transmission added to the system in each case.

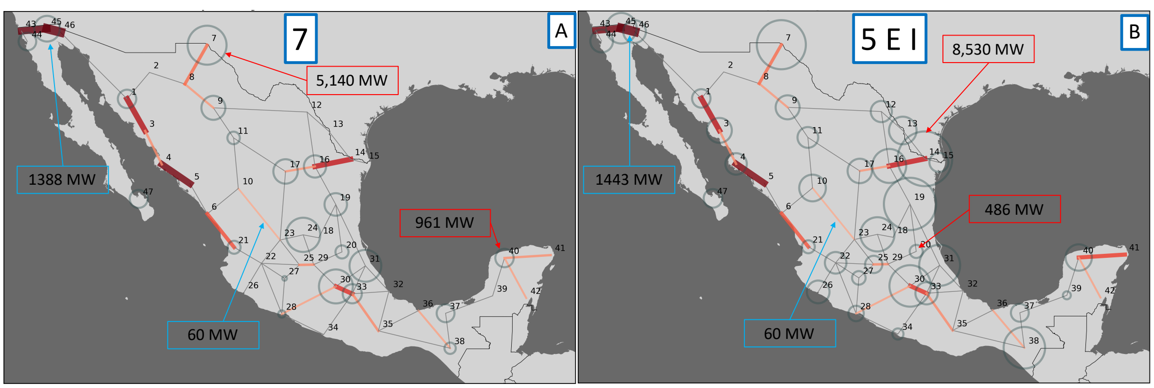


Figure 18. MIG with Minimum Expansion to Transmission in Mexico 2050
Small numbers at each node indicate demand or production points within the system, size of node represents amount of installed capacity. Grey transmission lines have not been expanded from 2016-2050 and the thickness of the red lines indicate the amount of expansion to each connection. Blue boxes indicate expansions to transmission lines. Red boxes indicate amount of installed capacity at node.

Figure 18 shows that even though MIG changes greatly from scenario 7 to 5-E-I the minimum expansions to the transmission system are almost identical. The largest difference between the two scenarios is line (40-41) in south east Mexico. This indicates that expansions to the transmission system are more robust across scenarios than expansions to installed generation capacity. We believe that the robustness of transmission expansions across IAM expansion plans can be attributed to the assumption in the PEGyT model that the distribution of the load within Mexico does not change over the planning period. This means that the relative distribution of load within the electrical grid will not change from 2016-2050.

The information provided in Figure 18 can provide insight to decision makers on identifying what areas of the grid will tend to be energy importers and which will be exporters. For example, we observe in Figure 18 that Merida (40) will always have generation plants, and that lines (40-41) and (40-42) will always be expanded. This implies that the Mexican government can make plans for developing generation capacity here as well as expand transmission lines in this area. We can also deduce that node 40 will tend to be an energy exporter while 41 and 42 will be importers. Similar behavior can be observed in nodes 7, 30 and 38 among others.

2.7 Limitations

There are some limitations to keep in mind for this work. As a colleague mentioned, "optimization kills for penny," meaning that differences in the location of generation may reflect very small cost improvements. Thus, it is possible that more robustness could be identified if cost minimization was slightly relaxed. Our initial analysis indicates, however, that the locations of the generation capacity are driven most strongly by constraints on the location of resources, and thus is likely to change very little. Additionally, the PEGyT model is able to characterize a wide range of generation technologies, but makes simplifications in representing the intermittency of renewable technologies in order to have permissible run times. This could impact results on investments in transmission. However, the combination of methods employed by PEGyT, including regional reserve requirements, seasonal load duration curves and capacity factors for renewables, and nodal constraints on expansion, have shown to have a high empirical accuracy. Moreover, inspection of our results related to transmission show that they are not driven by the expansion plans with high renewable penetration, which would be most susceptible to errors related to the representation of intermittency. This gives us a high level of confidence in the results presented in this paper.

2.8 Conclusions

In this study we provide a decision-relevant multi-model multi-scale approach to energy planning to meet climate goals, developing spatially and temporally detailed expansion plans for the Mexican electrical grid using the results from seven high-level top-down Integrated Assessment Models. By combining results from bottom-up and top-down models we can better understand the benefits and tradeoffs for different energy portfolio deployment for climate change mitigation. We also systematically compare these plans to identify where there is robustness and where flexibility is of the essence.

Many countries include energy diversity as one of their goals, with reasons including concerns about depletion of energy reserves, uncertainty of future fuel prices, disruptions to fuel supply chains, and fuel import dependency [32]. This study uncovered another reason, at least for Mexico: that more diverse portfolios lead to lower transmission intensity. This is because many technologies face geographic constraints on where they can be located, meaning that countries that rely on a small number of technologies are likely to need more transmission to get the electricity to demand centers. This is important because transmission tends to be difficult to plan and build. Moreover, reducing needed transmission helps reduce transmission and distribution losses, which have significant emissions impacts [19]. This finding, is highly dependent on geographical specificity not available in the top-down IAMs, and highlights the value of our approach.

We find that for Mexico, near-term transmission investments are fairly robust, with agreement on over 7 GW of investments across all 7 models. This is good news, since transmission is nearly always directed by the state and requires long planning horizons. The geographic locations to deploy specific generation technologies are less robust, but this may be less of a concern, since the specific location and type of generation can respond through market mechanisms. We did identify at least 20 GW of wind deployed in robust locations across the five less extreme expansion plans. Identifying the location of large generation sites such as wind farms can inform Mexico's planning process, allowing for the state or private companies to work on public engagement in the areas that have large robust investment. This can greatly help with community acceptance and engagement, which have proven to be difficult roadblocks for some energy projects.

While this multi-model approach to identifying robust development was applied to the Mexican electrical grid, this methodology can be expanded to other countries and regions to inform national-level climate and energy policy. By connecting insights from multiple top-down models with the geographic and temporal specificity of a bottom up model, we can provide better information for decision makers for development of future energy policies in efforts to reach long term climate change goals.

CHAPTER 3

ESSAY 2: CARBON CAPTURE AND STORAGE NETWORK EXPANSION PLANNING

3.1 Abstract

In efforts to reach long term climate change goals, many countries are looking at ways to decarbonize their electricity system. Carbon capture and storage (CCS) technologies offer an opportunity to reach these goals without drastically changing the electricity system. To incorporate large amounts of CCS technologies into the electrical grid, it is necessary to develop CO_2 transportation and storage infrastructure. In this essay, we present a Mixed Integer Linear Program (MILP) network expansion model for the creation of a CCS network. We apply this model to explore the CCS network for a series of expansion plans to the electricity system in Mexico. Overall, we find little agreement on which pipeline connections are built and where CO_2 is stored across scenarios. This result is mostly driven by the fact that there is little agreement across scenarios on the location of carbon capture. Because of this, careful consideration should be taken before committing to investments in specific CCS pipelines.

3.2 Motivation

When considering generation portfolios that depend heavily on carbon capture and storage (CCS) technologies, it is critical to consider what changes secondary systems, such as pipelines for the transportation and storage of captured carbon, will require. In this essay we set up a Mixed Integer Linear Program (MILP) cost minimization network expansion model that finds the optimal expansions to a CCS storage network for a series of future scenarios. This information is used to identify critical infrastructure in potential CCS networks and inform policy development.

3.2.1 Background on Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) is a process in which carbon dioxide (CO_2) is captured at a source, such as fossil fuel power plants or industrial plants, and subsequently transported to a permanent storage facility. In the last two decades there has been an increase in interest for CCS technologies due to growing concerns regarding climate change and increasing efforts to reduce emissions originating from the electricity sector. CCS technologies can provide a steppingstone to decarbonizing the electricity system without having to radically change the power system as we continue to develop more competitive renewable energy sources.

There are various types of CO_2 capturing systems including: post-combustion, pre-combustion, chemical looping and oxyfuel combustion. Current CCS technologies can capture between 85-95% of the CO_2 produced from a power plant. Adding this system to a power plant will require 10-40% more energy to an equivalent rated plant without CCS due to the energy required in the capture and compression process [50]. As Mexico sets its long-term climate change goals the government has begun to consider CCS technologies alongside of renewables in their efforts to decarbonize the electricity sector. Mexico has two main motivations in considering CCS technologies: using the injection and storage of CO_2 for improved oil recovery as well as meeting their long-term climate change goals [29].

It is necessary to develop supporting infrastructure to transport the captured CO_2 to storage sites. Depending on the scale of the application and distances required to transport, trucks, cargo ships, trains, and pipelines can be used as means of transportation of the captured CO_2 to storage sites [50]. In this study we focus on developing an optimal pipeline network for the transportation and storage of CO_2 given various expansion plans for the electricity system.

To create these CCS networks, it is necessary to have region specific data on geological and storage capabilities. Studies such as [30] have started to analyze the potential of CO_2 storage in the US and North America. Other studies [28, 29, 31] have performed preliminary analysis on the volcanic, geological, lithologic, seismic and tectonic characteristics of Mexico's territory to help identify exclusion zones where storage is not recommended, as well as areas for potential storage where further study is required, presented in Figure 19. Mexico, with its growing interest in CCS technologies, has also joined the North American Carbon Storage Atlas (NACSAP) in 2012. The goals of this collaboration are to:

- Facilitate the exchange on information of emission sources as well as potential storage sites for the elaboration of maps.

- Create a consensus on methodologies used to estimate the storage capacity of different geological resources in North America, one goal being making cross-border storage easier.
- Promote the collaboration in research and development of technology in the capture and storage of CO_2.

Figure 19. Zones of Geologic Carbon Storage Potential Source: DOE, Natural Resources Canada, and SENER, source: "The North American Carbon Storage Atlas," 2012.

The exclusion zones shown in Figure 19 in red are not considered favorable for CO_2 storage due to their high levels of tectonic, seismic and volcanic activities. The inclusion zones shown in green are considered geologically stable areas which offer the best potential for storage although more geological studies are required.

Figure 20. Saline Formations in Mexico. Source: DOE, Natural Resources Canada, and SENER, source: "The North American Carbon Storage Atlas," 2012.

It is currently thought that saline formations are Mexico's best potential resource for CO_2 storage. Saline formations are deep saltwater reservoirs composed of rocks with porous spaces filled with brine. Since CO_2 behaves like a liquid and allows for greater storage in greater depths, the reservoirs should be at a depth of at least 800 m [31]. Figure 20 shows the location of Mexico's saline reservoirs, mostly located near the eastern coast of the country. Preliminary studies, focusing on 111 sites, estimate that Mexico has the capacity to store 100 Giga-tones of CO_2 in its saline formations as shown in Table 9 [31].

Table 9. Estimated CO_2 Storage Potential per Site

Geological Province	Estimated Storage Potential Giga-Tones of CO_2	Node
Chihuahua	<1	48
Coahuila	13	49
Central	<1	50
Burgos	17	51
Tampico Misantla	10	52
Veracruz	15	53
Southeastern	24	54
Yucatan	14	55
Chiapas	6	56
Total	100	

3.3 Research Question

These are the main research questions for this essay: considering a series of expansion plans for the electricity grid, are there robust near-term investments in a CCS network? How does the optimal network vary with different expansion plans? Are there areas where CCS networks could potentially impact marginalized communities?

3.4 Methodology

In this essay, we develop and implement a MILP network expansion model to create and expand a CCS pipeline network. The model is solved with CPLEX 12.9. This model develops an optimal CCS pipeline network for each of the seven energy expansion plans for the electricity system presented in Essay 1. We calculate the amount of CO_2 entering the system at each node and year from 2016-2050, for each of the expansion plans from Essay 1. The CO_2 in each expansion plan depends on how much energy is produced by each CCS generation technology, as shown in Figure 21.

In this analysis we consider four CCS electricity generation technologies: oil, gas, coal and biomass. Each CCS technology has emissions characteristics in tons/GWh, in which 90% of the CO_2 emissions are captured for future storage, as presented in Table 10 [54]. The data from Table 10 is used to calculate how much CO_2 will be stored in each scenario based on the electricity produced per node and technology. Figure 21 presents the total electricity produced per CCS technology and how much CO_2 has to be stored in each IAM expansion plan. This figure also highlights the impact that different CCS portfolios have on the amount of CO_2 that has to be stored in each scenario. For example, TIAM has to store less CO_2 overall even though POLES produces more electricity with CCS technologies. This is because TIAM has a higher contribution of coal and biomass with CCS compared to POLES. Coal and biomass with CCS produce almost twice the CO_2 that gas with CCS does as shown in Table 10.

Based on the amount of CO_2 entering the system at each node and time period, the model will choose 1) where and when to build new, or expand existing, pipelines; 2) the capacity of each line; 3) which storage sites the CO_2 will be moved to. The network we analyze consists of 23 nodes as potential locations for CCS generation plants and nine potential storage sites, as shown in Figure 22. The estimated storage capacity for each of the nine storage sites is presented in Table 9 [31]. Study [31] does not provide detailed geographic data for the various storage areas in Table 9. Because of this, we estimated the location of each storage site to be at the center of each state or region defined, while ensuring that they were outside of major population centers.

Table 10. CO_2 Emissions per Electricity Generation Technology (NREL), "Annual Technology Baseline (ATB) Spreadsheet," 2019

Generation Technology	CO_2 Emissions tons/GWh		
	Conventional	With CCS	Stored
Coal	359	35.9	323
Natural Gas	199	19.9	179
Biomass	359	35.9	323
Oil	359**	35.9**	323**

** Oil plants are assumed to have the same emissions characteristics of a coal Plant.

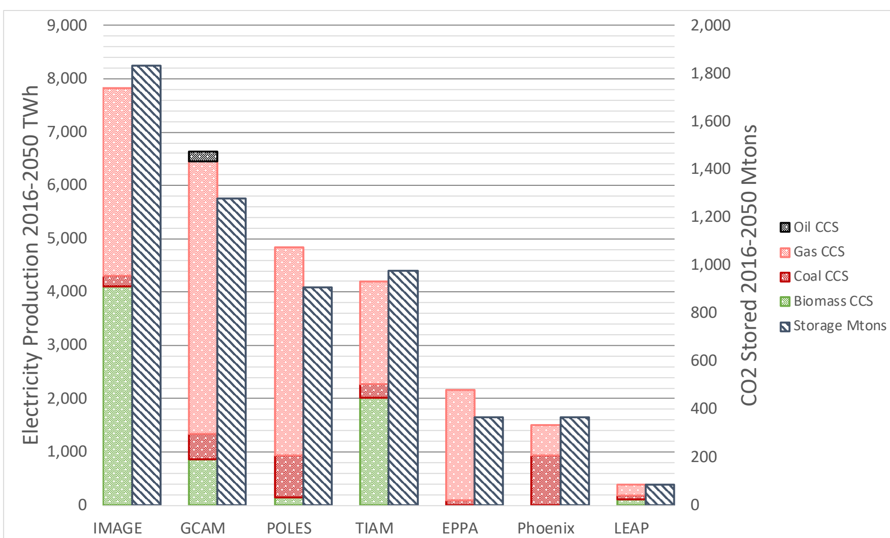


Figure 21. Electricity Produced (TWh) by CCS Technologies and CO_2 stored in Expansion plans 2016-2050

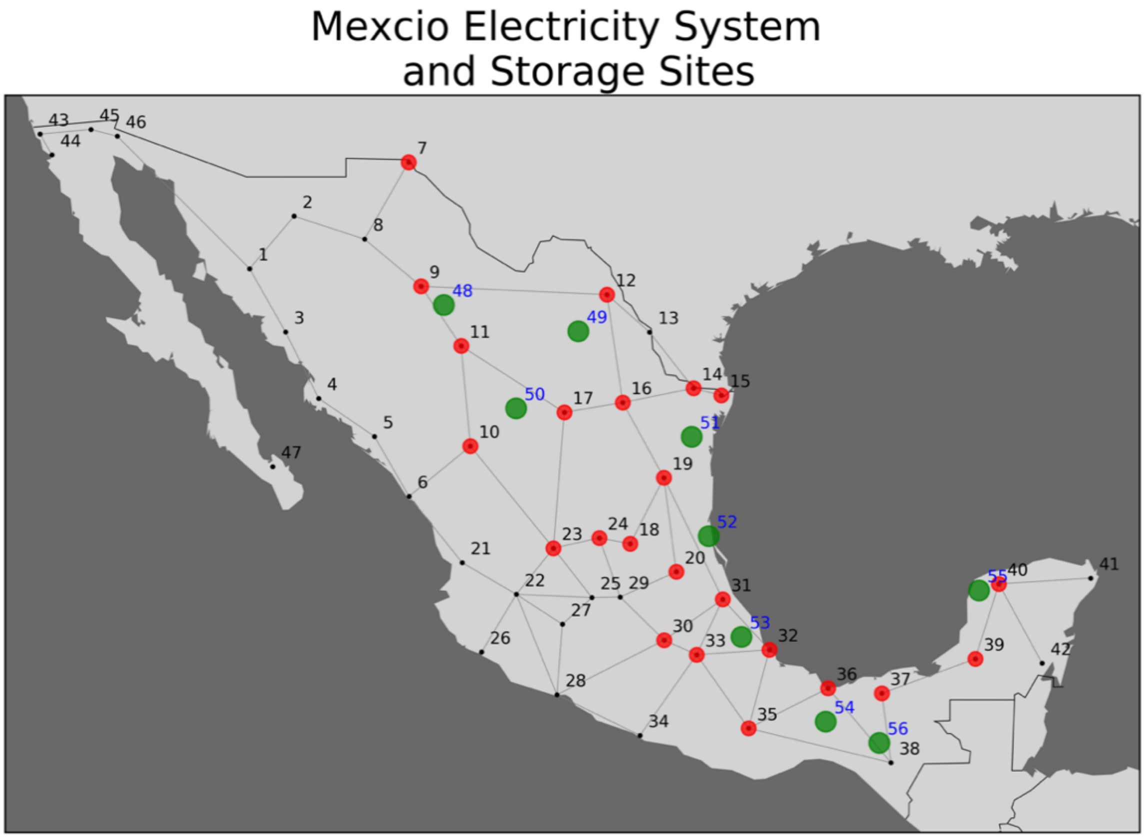


Figure 22. Mexican Electrical Grid and Storage sites

Black nodes indicate potential generation or demand nodes within the electricity grid. Red nodes indicate nodes within the electricity grid where CCS generation plants can be deployed. Green nodes indicate potential CO_2 storage sites. Grey lines indicate connections within the transmission system.

3.4.1 Model Formulation

The network expansion model chooses when to build new connections or expand existing pipelines. The key decision variable in the model is F_{nmt}^{exp}, which denotes the expansion of the line between nodes n and $m$at time period t in $kilo$Tons/hr of CO_2. This decision variable dictates the diameter of the pipelines within the system. N is the set of nodes within our system, F is the set of possible connections within the system and T is the set of time steps, which are the individual years from 2020-2050. Defining E_{nt} as the CO_2 entering the system at node n in *kilo*Tons of CO_2 at time period t and S_n^{max} as the maximum storage capacity at node n *in kilo*Tons. If a node n has CO_2 entering the system, because of electricity production from a CCS plant, we will refer to it as a source node and it will have $E_{nt} > 0$ and $S_n^{max} = 0$. This means that source nodes in the system do not have storage capacity. If a node n has storage capacity for CO_2, due to its geological characteristics, then we will refer to it as a storage node and it will have $E_{nt} = 0$ and $S_n^{max} > 0$.

The other decision variables within the model are: f_{nmt} the flow from node n to m in *kilo*Tons/hr at time period *t,* F_{nmt}^{max} maximum flow capacity in *kilo*Tons/hr from node n to m at time period *t,* s_{nt} new CO_2 stored at node n in kilotons at time *t,* S_{nt} the cumulative CO_2 stored at node n in kilotons and time period *t.* B_{nmt} is a binary decision variable that indicates if a line from node n to m is constructed (1) or not (0) at time t, and D_{nm} is the diameter of the pipeline in meters. The D_{nm} of each pipeline is determined by the maximum flow f_{nmt} between each pair of nodes. The relationship between the flow and diameter is nonlinear (see equation 10 below); thus we implement a piecewise linear function to approximate the pipeline diameter.

The MILP model formulation is presented below:

Objective Function:

$$\min_{F_{nmt}^{exp}} \sum_{t \in T} \sum_{n \in N} \sum_{m \in M} \frac{C * D_{nm} * l_{nm} + B_{nmt} * C_{fixed} * l_{nm}}{(1+r)^t} \tag{8}$$

s.t.

$$E_{nt} + 8760hr\left(\sum_m f_{mnt} - \sum_m f_{nmt}\right) - s_{nt} = 0, \qquad \forall t \in T, \forall n \in N, (n,m) \in F \qquad (9)$$

$$D_{nm} = \sqrt{\frac{4F_{nmt}^{exp}}{\upsilon\pi\rho}} \qquad (10)$$

$$S_{nt-1} + s_{nt} = S_{nt} \qquad (11)$$

$$S_{nt} \leq S_n^{max} \qquad (12)$$

$$f_{nmt} \leq F_{nmt}^{max} \qquad (13)$$

$$F_{nmt-1}^{max} + F_{nmt}^{exp} \geq F_{nmt}^{max} \qquad (14)$$

$$B_{nmt} + B_{mnt} \leq 1 \qquad (15)$$

$$\mathrm{H} * B_{nmt} \geq F_{nmt}^{exp} \qquad (16)$$

Parameters:

E_{nt}- CO_2 entering system at node *n* in *kilo*Tons of CO_2 at time period *t*

C- constant cost factor for the cross section of pipeline per unit of diameter per unit of length $^{\$}/_{m^2}$

C_{fixed} – fixed cost per unit of length, irrespective of the diameter, of building a new line $^{\$}/_{m}$

l_{nm}- distance from node *n* to *m* in m

S_n^{max}- Maximum storage capacity at node *n in kilo*Tons

M– Big M

N – set of nodes in the system

T – set of timesteps, 2020-2050

Decision Variables:

f_{nmt} – flow from node n to m in *kilo*Tons/hr at time period t

F_{nmt}^{exp} – capacity increase to line n m at time period t in *kilo*Tons/hr

F_{nmt}^{max}- maximum flow capacity in *kilo*Tons/hr from node n to m at time period t

$$B_{nmt} \begin{cases} 1, & if\ F_{nmt}^{exp} > 0 \\ 0, & otherwise \end{cases}$$

s_{nt}- CO_2 injected at node n in kilotons at time t

S_{nt}- Cumulative CO_2 stored at node n in kilotons and time period t

D_{nm} − diameter of the pipeline (m)

The objective function (8) of the model minimizes the sum of variable and fixed costs for constructing a CCS network, which are driven by D_{nm}, over the planning period. To calculate the diameter in meters, we use equation (10). Here v is the velocity of the flow within the pipeline in m/s and ρ is the density of the CO_2 in kg/m^3. We assume the velocity of the CO_2 through the pipeline to be 1.5 m/s, this is within the range of cost-effective velocities for dense phase CO_2 $(1.5 - 2\ m/s)$ [56]. The density ρ of the CO_2 in the pipelines is assumed to be of 800 kg/m^3 [56]. As the relation between the diameter and the flow through the pipeline is nonlinear we use a piecewise function within our objective function, as shown in figure 23.

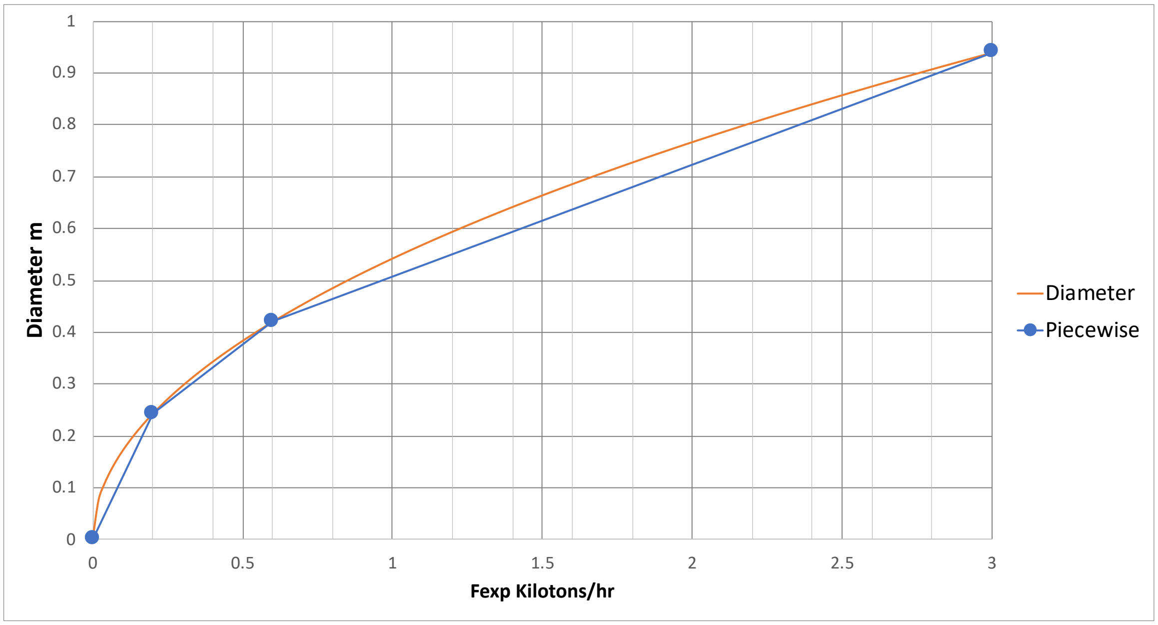


Figure 23. Diameter of Pipeline m vs F_{nmt}^{exp} kilotons/hr

The fixed costs in the objective function are associated with purchasing land and building pipelines, whereas the variable costs are related to the capacity of each pipeline built. The variable cost component of the objective function is based on linear cost models such as those established in [55]. We are using a cost factor C for the pipelines of 1443 $\$_{2016}/m^2$, this number is based on a linear regression of uncorrected Federal Energy Regulatory Commission (FERC) cost data [55].

Constraint (9) ensures conservation of mass within the system so that all the CO_2 entering the system has to be stored at a storage node. Constraints (11) and (12) keep track of the cumulative storage at each node and ensure that the total CO_2 stored at each node (S_{nt}) does not exceed the storage capacity (S_n^{max}) for that node. Constraints (13) and (14) set the maximum flow capacity for each line (F_{nmt}^{max}) within the system and required expansions for the capacity of a line (F_{nmt}^{exp}). Constraint (15) allows for only one line to be built between any two points *n* and *m*. Finally, constraint (16) uses a binary variable to indicate when the model expands the capacity of a line within the system.

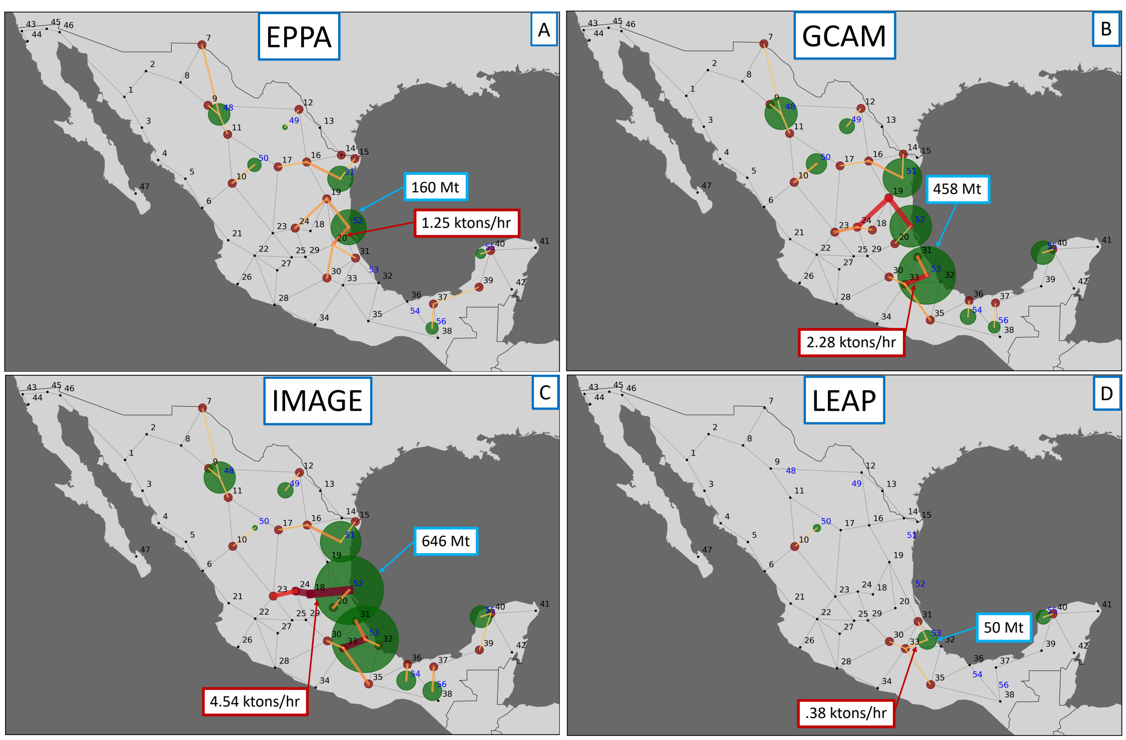
3.5 Results

We now analyze the carbon capture and storage networks created by the MILP model for each of the expansion plans to the electricity system in Mexico presented in Essay 1. Our interests are to understand the overall behavior of the CCS networks, identify the potential robust investments across CCS networks in different expansion plans, as well as to determine possible complications of creating different CCS networks near marginalized communities or protected areas.

Figure 24 shows the CCS networks created for each IAM expansion plan. We see a wide variety of configurations for the networks as each expansion plan has different active source nodes with CCS plants. These differences are driven by the distinctive generation portfolios, the geographic limitations that each generation technology has, and the overall distribution of load within the system. The distribution of natural gas and coal plants are determined by the infrastructure available for the transportation of fuel. Biomass plants are limited to central and southern states, outside of the northern more arid states where it would be harder to locally grow and cultivate biomass feedstock.

We find that these limitations on the location of electricity generation affect the distribution of how much CO_2 is stored at specific storage site, as shown Figure 25. We find that half of the expansion plans, IMAGE, GCAM, POLES and TIAM, concentrate most of the CO_2 stored in nodes 52 and 53, which are located in central Mexico close to the Gulf of Mexico. This can be attributed to the fact that these expansion plans use biomass with CCS, which are restricted to central and southern Mexico. Another contributing factor is that these storage sites are the closest to some of the largest load centers within the Mexican electrical grid, such as Mexico City, Puebla and Queretaro so by necessity require large amounts of electricity production at or near these nodes.

Expansions to Carbon Capture and Storage Systems 2050



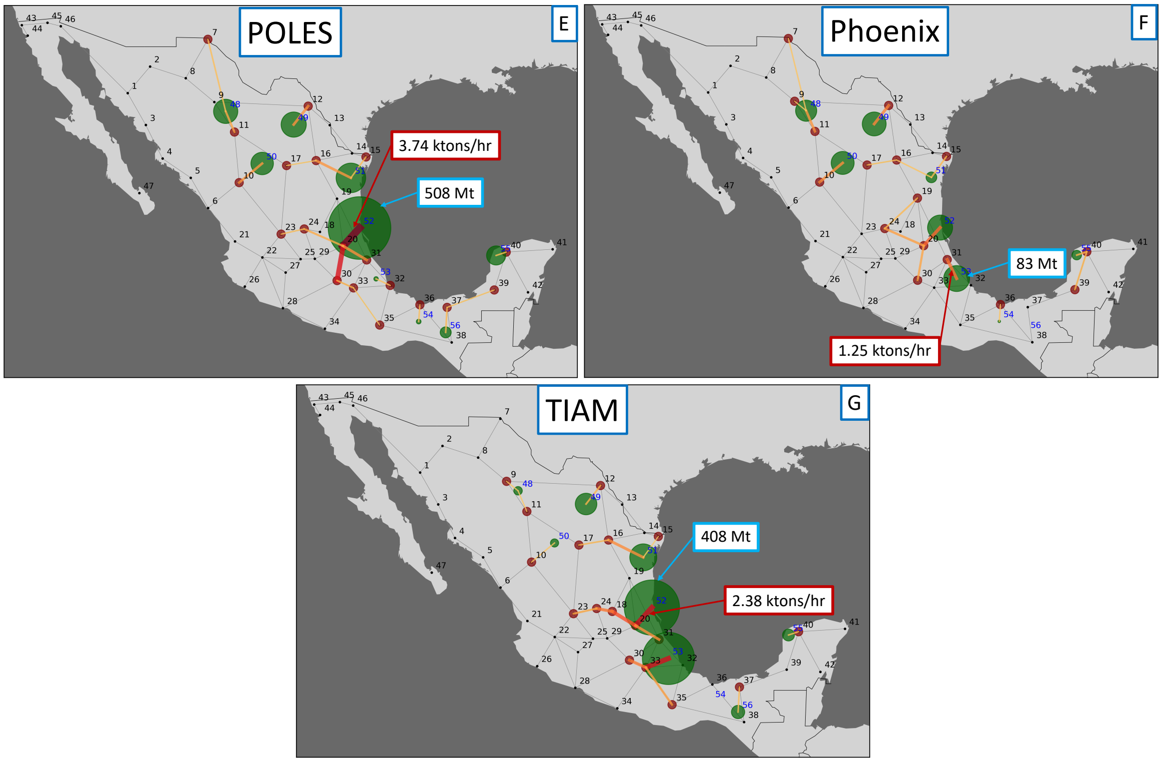


Figure 24. Expansions to CCS Network 2016-2050

Black nodes indicate potential generation or demand nodes within the electricity grid. Red nodes indicate nodes with CCS generation plants. Green nodes indicate CO_2 storage sites and the size represents the amount of CO_2 stored there. Grey lines indicate connections within the transmission system and red lines indicate connections within the CCS pipeline network.

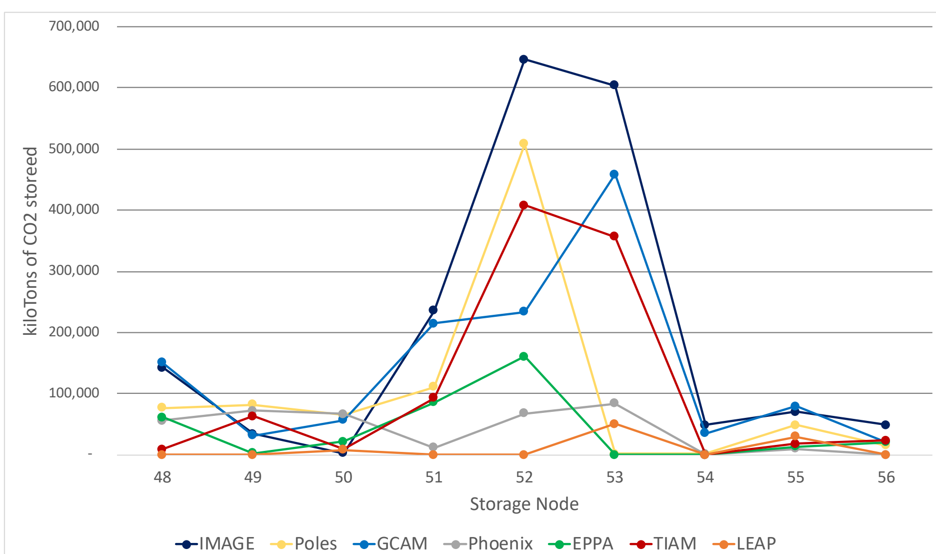


Figure 25. CO_2 Stored at each storage node in kilotons for each Expansion Plan

3.5.1 Robust Connections

We are interested in identifying potential robust connections within the CCS network across different expansion plans. Similar to the first essay, we define robust connections within the CCS network as the minimum amount of installed pipeline flow capacity in kilotons/hr. These connections between nodes represent investments that we can be confident in despite uncertainties regarding the development of the electricity system.

In our analysis we find that there is little robustness in the investments in CCS pipelines across the expansion plans compared to the high levels of robustness that we had in transmission expansions in Essay 1. Even when omitting the three scenarios with the lowest amounts of CO_2 to be stored, LEAP, Phoenix and EPPA, we find very little robustness across expansion plans. These three expansion plans were omitted as they each require storing less than half of the CO_2 that POLES and the other remaining expansion plans require. With only 11 lines in common across the remaining 4 expansion plans, as shown in Figure 26, we have 1,500 km of robust pipeline. This is 62% of the TIAM scenario, which has the lowest CCS network length among the four expansion plans (2,400 km of pipeline, as shown in Figure 27). On the storage side there is agreement on the storage location for 493 Mtons of CO_2, where POLES, the expansion plan with the lowest requirement for total CO_2 storage, has 910 Mtons of CO_2.

As there is little agreement across the scenarios this tells us that there is more uncertainty in the development of CCS pipeline networks. This can largely be attributed to the fact that in Essay 1 we find little robustness in investments in generation capacity for specific technologies. This affects the robustness of the CCS network, as the location of CCS plants will affect the characteristics of the network. This means that once a decision is made on which pipelines to create and develop for storage, decision makers will have to commit to it as they have less flexibility to change portfolios or decisions.

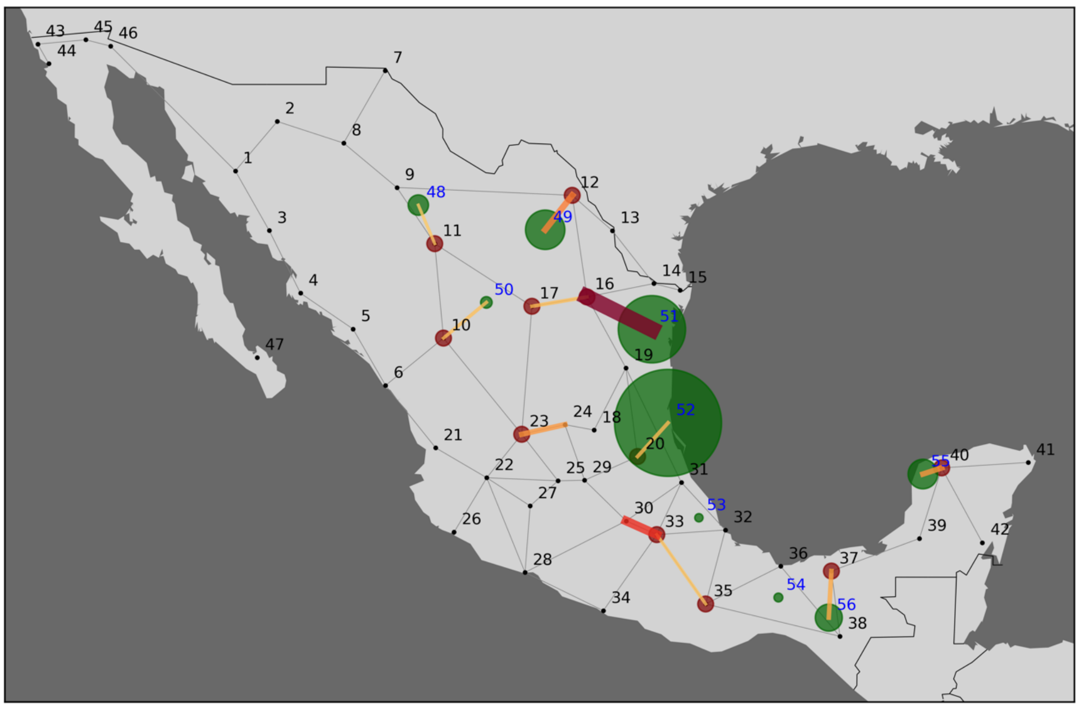


Figure 26. Robust Expansions to CCS Network 2016-2050 with 4 scenarios

Black nodes indicate potential generation or demand nodes within the electricity grid. Red nodes indicate nodes with CCS generation plants. Green nodes indicate CO_2 storage sites and the size represents the amount of CO_2 stored there. Grey lines indicate connections within the transmission system and red lines indicate connections within the CCS pipeline network.

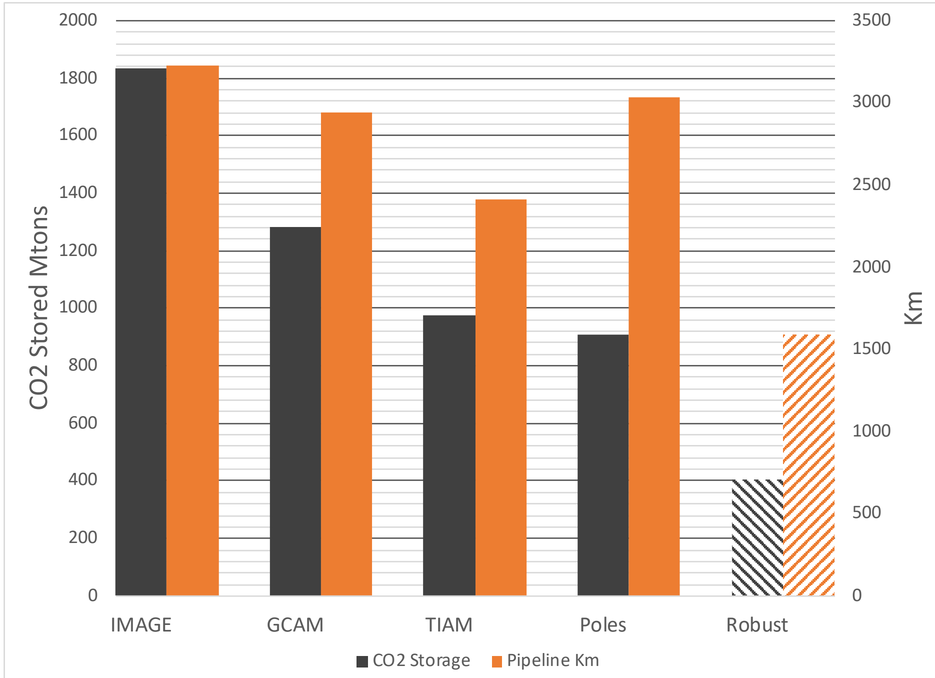


Figure 27. CO_2 Stored and km of pipeline for each Expansion Plan
Robust columns indicate the km of pipeline and CO_2 stored on which there is agreement between IAM expansion plans IMAGE, GCAM, TIAM, Poles

3.5.2 Effects on Indigenous and poor communities

In any large infrastructure project, it is important to recognize local economies, geographic conditions, social and political environments as well as to involve all potential stakeholders. In this section we highlight areas where indigenous communities within Mexico may be affected by the development of CCS pipeline networks so that decision makers can integrate this into the decision-making process.

Figure 28 shows that some of the robust connections within the CCS pipeline network located in states with large indigenous populations such as Oaxaca, Chiapas, Veracruz and Yucatan. If we look at individual expansion plans, in Figure 24, TIAMs, POLES, IMAGE and GCAM have relatively higher development in these areas. To help prevent conflicts with local communities in the development of these projects it is critical to ensure that local groups are integrated into the decision-making process. In the past Mexico has had difficulties with local communities in developing energy projects because of poor communication and rushed permitting processes. One example of this occurred with the development of wind farms in the region of the Isthmus of Tehuantepec in Oaxaca, Mexico. One of the windiest places in the country, and with a large indigenous population, this region witnessed intense social unrest in response to the wind farm initiatives, which garnered national and international coverage, resulting in the delay and relocation of several projects. Previous studies [51,52] have looked into this case and have identified that the absence of land planning rules, conflict resolution mechanisms of property rights and poor communication, led to conflicts with local communities.

More specifically regarding key barriers specific to the development of CCS networks there is: Lack of public knowledge about CCS technologies, poor communication strategies, lack of long term policy of CCS implementation, lack of trust from stakeholders, Not In My Back Yard (NIMBY) reaction, site selection and project design without taking into account the specific local conditions and the appearance of protest potential due to negative public perception [53]. To ensure proper sustainable development for all communities within Mexico, it is essential to implement lessons learned from previous energy projects in the country and abroad.

Most importantly that requires establishing proper communication mechanisms between all parties and involving all stakeholders from the outset.

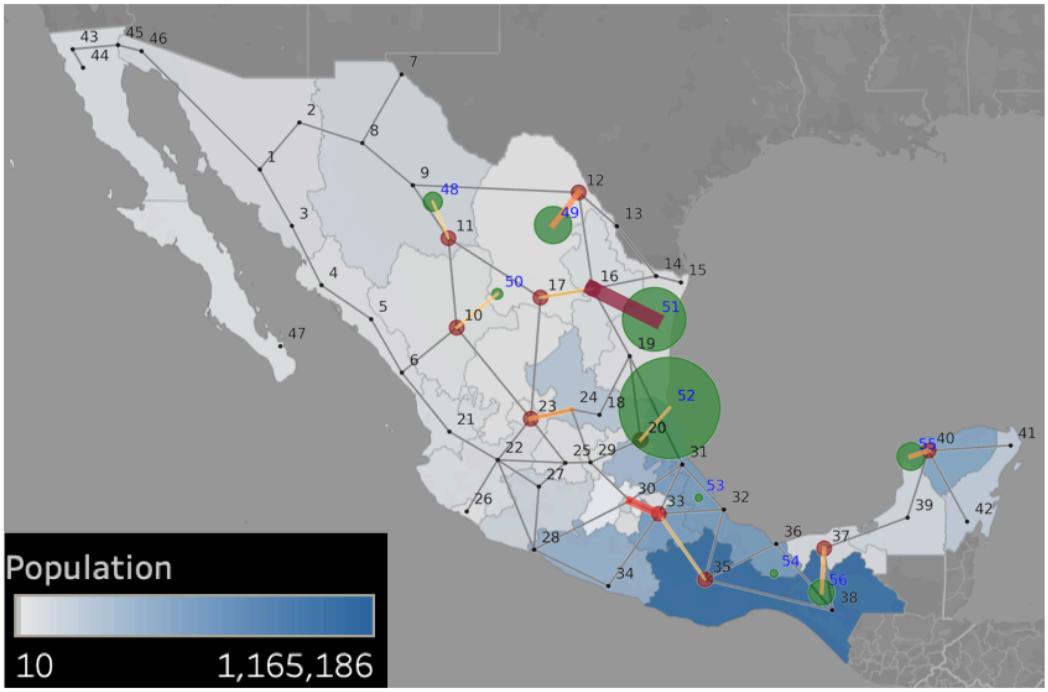


Figure 28. Indigenous population per state and robust expansions to CCS Network
Black nodes indicate potential generation or demand nodes within the electricity grid. Red nodes indicate nodes with CCS generation plants. Green nodes indicate how much CO_2 stored at each site. Grey lines indicate connections within the transmission system and red lines indicate connections within the CCS pipeline network. The blue color indicates the size of the indigenous population per state.

3.6 Limitations

It is important to point out some of the limitations of this study. As CCS technologies are just starting to be considered for future development in Mexico there have only been preliminary studies in potential underground storage sites for CO_2 [29,31], as shown in Table 9. More detailed data on storage site locations and capacity could have a significant impact on pipeline network configurations and would allow us to model more realistic CCS networks. Additionally, we determine the capacities for the CCS pipeline connections with average flow in $kilo\ tons\ CO_2/hr$ based on the annual CO_2 entering the system at each node. This is because the PEGyT model provides information on annual electricity produced per technology but not on an hourly basis. This prevents us from being able to determine the peaks of CCS electricity production and hence the peaks of CO_2 entering the system. As a result, our analysis is likely to underestimate the necessary flow capacities for the CCS pipeline connections. Finally, we use a simplified transportation model that does not take into account the physics of flows within pipeline networks such as pipeline pressures, temperature, booster stations, roughness height, etc. In future work results from our simplified model could be used to provide an initial CCS network configuration to a more detailed physics model to finish the network optimization process.

3.7 Conclusions

In this essay we present a mixed integer linear programming (MILP) model for the network expansion of a carbon capture and storage pipeline network to minimize the total cost. We provide the model with estimates on the location and capacity of potential CO_2 storage sites to try and best reflect the actual CO_2 storage potential of Mexico. With this model we create a series of optimal CCS networks that would be required for the operation of each of the expansion plan presented in Essay 1. In each of the expansion plans the mix of CCS generation technologies and their geographic distribution have a strong impact on the characteristics of each CCS pipeline network.

We compared the CCS pipeline networks created for each of the expansion plans and found little agreement on which pipeline connections are built and where CO_2 is stored. Even when we omit the three scenarios with the lowest levels of CO_2 production, LEAP, Phoenix and EPPA, there is little agreement across the CCS networks. When analyzing the remaining 4 expansion plans, we find agreement on 11 lines which are equivalent to 1,500km of robust pipeline compared to the 2,400-3,100km required for the remaining expansion plan. There is also little agreement on where the CO_2 will be stored, with agreement on 493 Mtons while most expansion plans require between 900-1,800Mtons. We believe that overall the driving factor of this disagreement is that there is little agreement on the location of specific generation technologies. This will directly impact the CCS networks as it depends on the location of CCS generation plants and how much electricity they produce.

We find that there are robust expansions to the CCS pipeline network within states with high indigenous populations and high poverty rates such as Veracruz, Chiapas and Oaxaca. Historically these areas have seen unrest and pushback against large energy projects, in large measure because of poor communication and management. When developing these projects, awareness of social and political factors is paramount. For the successful development of any of these potential CCS networks it is necessary to have good communication and engagement with local communities ensuring that there are proper channels for people to express their concerns and desires. Further work has to be done finding better ways of integrating local and often marginalized communities into the decision-making process.

This study helps to highlight the importance of considering the development of secondary infrastructure when looking at long term energy planning, especially when considering a radical change in the electricity generation portfolio. Future work will be needed in developing a more detailed CO_2 network model as well as potentially combining this research with an analysis of natural gas pipeline network expansions.

CHAPTER 4

ESSAY 3: EVALUATING THE SUSTAINABILITY OF THE DEVELOPMENT OF THE ELECTRICAL GRID WITH MCDA

4.1 Abstract

In recent years due to growing concerns about the effects of climate change, energy planning has become an increasingly complex problem as stakeholders try to find sustainable solutions capable of meeting multiple and often conflicting objectives. Multi-criteria decision analysis provides a tool that allows decision makers to consider the tradeoffs between multiple aspects of sustainability for the energy system. For this study, we use seven criteria to evaluate the overall sustainability of a series of expansion plans to the electricity system. We incorporate geographic information provided by our models into the sustainability and equity analysis of various development pathways. We summarize the overall ranking of each expansion plan with the use of the weighted sum method. We find that expansion plans with high implementation of carbon capture and storage (CCS) technologies have the lowest sustainability scores overall. While CCS technologies have low Levelized Cost of Energy (LCOE) and GHG emissions, they have high air pollution and water-use levels and require the development of large CCS pipeline networks. These are tradeoffs that decisions makers must consider when looking at different development options.

4.2 Motivation

For this chapter we use a multi criteria decision analysis (MCDA) tool to evaluate the sustainability of the seven IAM's expansion plans developed in Essay 1 and the CCS networks created in Essay 2. Here an *expansion plan* refers to all the expansions to transmission and installed capacity within the electrical grid, as well as the annual electricity each power plant will produce from 2016 to 2050. We also take information provided by the CCS network expansion model from essay 2 regarding the amount of CO_2 stored and pipeline capacity expansions. All of this information is used in our MCDA analysis to evaluate the sustainability of our different development pathways, with the use of 7 sustainability criteria.

This study adds to previous efforts by taking advantage of the geospatial information provided by the PEGyT model; and by performing an equity analysis to study how various expansion plans might affect poor or marginalized communities. By combining all of this information, we calculate sustainability scores for each of the expansion plan. This process is summarized in Figure 29.

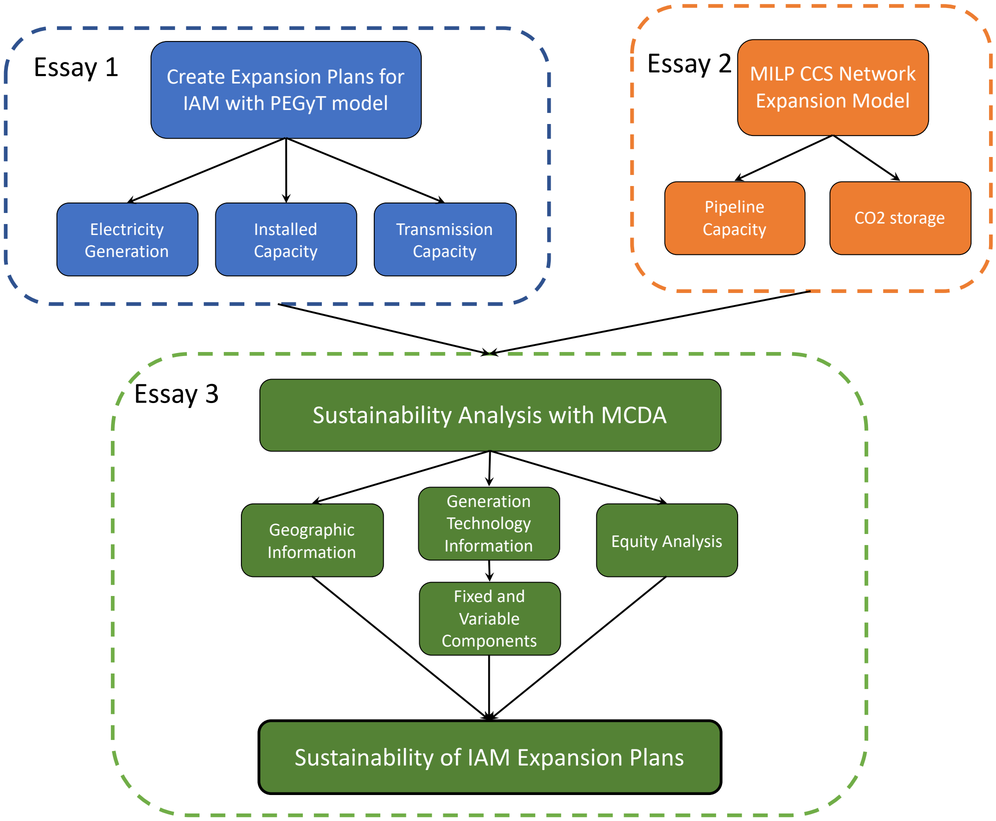


Figure 29. Outline for application of MCDA and RPDA

4.2.1 Multi Criteria Decision Analysis (MCDA) for Assessing Energy Systems

Multi criteria decision analysis is a powerful tool for informing decision makers (DM) when confronted with multiple and often conflicting criteria. This is often useful when evaluating the sustainability of energy systems where decision makers can have differing views. MCDA gives us quantitative tools to compare the trade-offs between economic, environmental and social aspects of different expansion plans for the energy system. It is important to keep in mind that with MCDA there is generally no one best solution and it will be subjective to the preferences of the decision maker.

When analyzing the sustainability of an energy system in a given country previous research has focused on different aspects of the system. Works such as [33] study the sustainability of Australian electricity generation system by focusing on evaluating their fossil fuel sources with a series of environmental, economic and social criteria. Other studies focus on evaluating the sustainability of specific generation technologies under a wide range of criteria such as [36] in the United States and [38] in Lithuania.

Other papers look at the sustainability of generation portfolios such as [35] which looks at 5 different electricity production scenarios for Portugal in 2020. Each portfolio is evaluated using a MCDA tool, the value of each scenario is calculated using an additive value function (AVF) considering 13 different criteria to rank the scenarios. In [34] they use MCDA to evaluate portfolios in the South African electricity sector. This paper also incorporates decision making under uncertainty to rank power expansion plans. Preferred portfolios were chosen based on their performance with regards to 4 indicators and confidence criteria.

Most similar to our study is [32], which uses MCDA to analyze the sustainability of the Mexican energy system in 2050. They use a multi-attribute value theory with 10 environmental, 3 economic and 4 social criteria to rank 11 generation portfolios for Mexico in 2050. This study does not provide a single best solution; rather, it identifies a set of 3 preferred portfolios. These portfolios only have 15% electricity coming from fossil fuels while the rest comes from nuclear and renewables. These results are in line with those presented in [3] in which all the portfolios have at least 80% renewable sources. Our sustainability analysis differs in that it is performed with a detailed model of the Mexican grid and evaluates the entire expansion plan created for each scenario, while [32] uses a simplified electrical model looking only at 2050. This will allow us to evaluate not just the generation portfolio in 2050 but the whole generation expansion plan from 2016-2050, as well as changes required in transmission and transportation networks for CO_2. In this way, we will be able to evaluate the whole expansion plan rather than just looking at a generation technology or portfolio.

4.3 Research Question

This essay explores the following main questions: How does the sustainability of various expansion plans compare when integrating geographic data into the analysis? What are the main driving factors for the overall sustainability score for the different expansion plans? What are areas of concern for equity within the different expansion plans? We provide detailed answers to these research questions by evaluating the sustainability of the expansion plans from the two previous essays with a MCDA tool.

4.4 Methodology

4.4.1 Criteria for Sustainability:

A set of criteria has been selected to evaluate the sustainability of each expansion plan. These criteria are meant to reflect the most important factors for the Mexican government. The 2014-2028 National Energy Strategy states that the two main objectives of the energy reforms are to facilitate *economic growth* and *social inclusion* by extending access to quality electricity services to the entire population [43]. Our criteria reflect the two pillars of this strategy, which are sustainability in the electricity sector and energy security.

More criteria will not necessarily lead to better decision making so it is important to cover all the areas of importance to the DM with as few criteria as possible. We incorporated the principles suggested by [40] when we defined our criteria for sustainable development. Each criteria should have these principal characteristics:

- Systemic – The set of criteria should reflect the most important characteristics of the energy system.
- Consistency – The set of criteria should be consistent with the needs of the DM.
- Independence – The criteria should not have inclusion relationship with any other criteria.
- Measurability – The criteria has to be measurable in a quantitative form or be able to be expressed qualitatively.
- Comparability – the criteria should be easily comparable to each other.

The following sub-sections define and justify the sustainability criteria that will be used to evaluate each expansion plan. They are presented in Table 11.

Table 11. Sustainability Criteria for Expansion Plans 2016-2050

Criteria	Unit
Air Pollution Emissions	tons/GWh
Water Use	L/GWh
Life Cycle GHG Emissions	tons CO_2eq/GWh
Land Use	m^2/GWh
Levelized Cost of Energy	$/GWh
Kilometers of Pipeline Built	Km*Capacity/GWh
Energy Diversity	0-1 (dimensionless)

Each generation technology used in the expansion plans will have an impact on the sustainability criteria presented in Table 11. We build of the work of [36] who defines the impacts to sustainability criteria in a per unit of energy basis and [45] who breaks down the effects on the sustainability criteria into a fixed and variable component. The fixed component of these criteria captures the impact of the installed capacity infrastructure on the various sustainability criteria. The variable component is related to how much electricity is produced by each generation technology. This break down into fixed and variable contributions to sustainability criteria permits us to more accurately capture the overall sustainability of each expansion plan.

A challenge in comparing the sustainability of the different expansion plans produced by the different IAMs is that they produce vastly different amounts of energy in the year 2050. It is not possible to directly compare most criteria such as water use, emissions, land use, investment costs and kilometers of pipeline built without unfairly penalizing expansion plans that produce larger amounts of electricity in 2050. We also do not want to favor expansion plans that produce higher amounts of electricity by assuming that higher electricity production is correlated to a higher quality of life. The IAMs have different electricity productions due to their assumptions on economic and population growth, energy saving initiatives and electrification of other industries (for a more detailed explanation refer to Chapter 2 section 2.4.1).

Because of this all of the criteria in Table 11, with the exception of energy diversity, will be evaluated on a per unit of energy basis, to allow for a more direct comparison between expansion plans. The criteria are presented in a per unit energy basis by calculating the value of the criteria for the entire expansion plan period and then dividing by the total amount of energy produced in the expansion plan. Thus, we are implicitly using a discount rate of 0 for the sustainability criteria, meaning that we care the same about the effects of emissions, water use, etc. in the year 2050 as to those in 2016.

In this study we are also interested in addressing questions of equity within sustainability when we are analyzing each expansion plan. We identify if the effects of climate change mitigation efforts are disproportionately affecting vulnerable communities, such as those below the poverty line or minority communities. Mexico's Special Program for Climate Change identifies that in Mexico around half of the population lives in poverty and around 68% of the population [57], mostly poor communities, have at one point or another suffered the effects of natural disasters.

This is due to the fact that poor communities tend to live in areas vulnerable to natural disasters, and hence climate change, such as living near riverbanks, mountain sides, and ravines [49]. Mexico's INDCs also recognizes the need to look at how climate change affects under-represented groups such as women and the importance of including them as decision makers [10]. With this analysis we want to ensure that in efforts to mitigate climate change we do not also disproportionately affect vulnerable communities.

A novel aspect of our study is that we are using geographic information to evaluate the sustainability and equity of an expansion plan. When evaluating air pollution emissions and water use for each expansion plan, we consider that these criteria are significantly affected by local factors such as available water resources and local population in the area when evaluating sustainability. We will consider local effects on sustainability by using weights for each node on air pollution and water consumption. This is further developed below.

4.4.1.1 Air Pollution Emissions

Our criteria, x_{ai} is the total weighted cumulative air pollution emissions per unit of energy (kg/GWh) for expansion plan i. Air pollution emissions are calculated as the combined life cycle emissions of SO_2, NO_x and particulate matter (PM) as in [36]. The emissions are calculated based on the annual installed capacity and electricity produced per technology at each node. x_{ai} is the summation of weighted air pollution emissions for all nodes a_{in}, where each node has a weight that reflects the percentage of the total national population at that node. We give a higher weight to nodes with larger populations as this implies more people are exposed to the air pollution and there will be more adverse health effects. We define the weighted cumulative air pollution emissions per unit of energy x_{ai} with equations (17) and (18):

$$a_{in} = \sum_{t=1}^{T}\sum_{g=1}^{G} k_{tngi} a_g^f + \varepsilon_{tngi}\, a_g^v\,, \forall i = 1, \dots, B_e \qquad (17)$$

$$x_{ai} = \frac{\sum_{n=1}^{N} \omega_n\, a_{in}}{\varepsilon_i^{total}}\,, \forall i = 1, \dots, B_e \qquad (18)$$

Where a_{in} are the total pollution emissions for the expansion plan i at node n, k_{tngi} is the new installed capacity at node n in year t of generation technology g in expansion plan i, a_g^f are the fixed pollution emissions for generation technology g, per unit of capacity. ε_{ntgi} is the electricity produced at node n at year t by generation technology g in expansion plan i, a_g^v are the variable pollution emissions for generation technology g, per unit energy. In equation (18), ω_n is the population weight for node n. The population weight for each node is defined as the percentage of the total population at node n. ε_i^{total} is the total cumulative electricity production for expansion plan i and B_e is the total number of expansion plans in this study. The population weights ω_n, a_g^v and a_g^f can be seen in the data section 4.7.

4.4.1.2 Water Use

Our criteria x_{ci} is total weighted water use per unit energy (L/GWh) for each expansion plan i. We define water use as water withdrawn from the environment that is not returned to its original source [36]. Water use is calculated using the annual installed capacity and energy produced per technology at each node, similarly to air pollution. The water consumption at each node is multiplied by a weight that reflects the area's water scarcity. The water scarcity for each area is defined as the amount of water withdrawn relative to the amount of local renewable water, as presented in equation (19). The higher the weight, the more severe the local scarcity, hence being less sustainable. We define the weighted total water consumption per unit of energy x_{ci} with equations (20) and (21):

$$\mu_n = \frac{H2O_n^{withdrawn}}{H2O_n^{available}} \qquad (19)$$

$$c_{in} = \sum_{t=1}^{T} \sum_{g=1}^{G} k_{tngi} c_g^f + \varepsilon_{tngi}\, c_g^v \,, \forall i = 1, \dots, B_e \qquad (20)$$

$$x_{ci} = \frac{\sum_{n=1}^{N} \mu_n \, c_{in}}{\varepsilon_i^{total}}, \forall i = 1, \dots, B_e \qquad (21)$$

Where c_{in} is the total water consumption of node n in expansion plan i, x_{ci} is the total weighted water consumption per unit of energy for expansion plan i (L/GWh), μ_n is the water scarcity weight for node n, c_g^f and c_g^v are the fixed and variable water consumption for generation technology g per installed capacity (L/MW) and per unit of energy (L/GWh). The weights for μ_n are given in the data section 4.7.

4.4.1.3 Life Cycle GHG Emissions

For each expansion plan we will consider x_{ei} the total cumulative life cycle GHG emissions, as CO_2 equivalent emissions per unit of energy, for all generation technology including the upstream, O&M and downstream CO_2, CH_4 and NO_2 emissions as in [36]. These GHG emissions are also calculated based on a fixed and variable component. The fixed and variable component for GHG emissions for each technology are presented in table 13 in the data section 4.7. The total GHG emissions per unit of energy are obtained with equations (22) and (23):

$$e_{in} = \sum_{t=1}^{T} \sum_{g=1}^{G} k_{tngi} e_g^f + \varepsilon_{tngi}\, e_g^v \,, \forall i = 1, \dots, B_e \qquad (22)$$

$$x_{ei} = \frac{\sum_{n=1}^{N} e_{in}}{\varepsilon_i^{total}} \,, \forall i = 1, \dots, B_e \qquad (23)$$

Where e_{in} are the total GHG emissions for node n in expansion plan i, x_{ei} are the total GHG emissions per unit energy for the expansion plan i, e_g^f are the fixed GHG emissions for generation technology g per installed capacity (kgCO_{2eq}/MW) and e_g^v are the variable GHG emissions for generation technology g per unit of energy (kgCO_{2eq}/GWh).

4.4.1.4 Land Use

For each expansion plan we will calculate the total life cycle land use x_{Li} for all generation technologies in terms of ${m^2}/{GWh}$. Land use is of importance to our study due to the environmental and social impacts that the development of new power plants can incur. We break down the land use for the different generation technologies into either a fixed or variable component depending on the characteristics of each technology. For renewable technologies (hydro, wind, solar, geothermal and nuclear) we consider a fixed component to land use L_g^f in ${m^2}/{MW}$ which is associated to the construction of a new generation plant. With conventional technologies (coal, gas, oil and biomass) we only consider a variable component to land use L_g^v in ${m^2}/{GWh}$ because the land use related to fuel extraction and production becomes significant across the lifetime of the power plant. From a social aspect land use can also be a concern as energy projects can have pushback from communities close to where these projects are being developed. For this study we consider that the lower the land use an expansion plan has the higher its sustainability score. The land use for each expansion plan is calculated using equation (24):

$$x_{Li} = \frac{\sum_{n=1}^{N} \sum_{t=1}^{T} \sum_{g=1}^{G} k_{tngi} L_g^f + \varepsilon_{tngi}\, L_g^v}{\varepsilon_i^{total}}, \forall i = 1, \ldots, B_e \qquad (24)$$

Where L_g^f is the fixed land use for generation technology g in ${m^2}/{MW}$ and L_g^v is the variable land use for generation technology g in ${m^2}/{GWh}$. Values for land use per technology were obtained from [36] and are presented in Table 13 in the data section 4.7.

4.4.1.5 Levelized Cost of Energy (LCOE)

The value for LCOE will be calculated with equation (25):

$$x_{LCOEi} = \frac{\sum_t \frac{I_{ti}^{total}}{(1+d)^t}}{\sum_t \frac{\varepsilon_{ti}^{total}}{(1+d)^t}} \qquad (25)$$

Where x_{LCOEi} is the LCOE for expansion plan i, I_{ti}^{total} represents the total investment in 2016 US dollars for period t in expansion plan i which includes overnight investments in generation and transmission capacity as well as O&M and fuel costs.

4.4.1.6 Kilometers of Pipeline Built

Our criteria represents the total volume of CO_2 pipeline: the length of pipelines in kilometers multiplied by the capacity of the pipelines. A lower volume is preferred. The units of this criteria are $km\frac{kiltons}{hr}\Big/_{GWh}$. The criteria is expressed in equation (26):

$$x_{\mathcal{L}i} = \frac{\sum \mathcal{L}_{nmi} * F_{nmti}^{exp}}{\varepsilon_i^{total}}, \forall i = 1, \dots, B_e \qquad (26)$$

Where $\mathcal{L}_{nmi}$ is the length of pipeline from n to m in the CCS network in expansion plan i, F_{nmti}^{exp} is the capacity expansion to line n to m at time period t in *kilo*Tons/hr in expansion plan i. The criteria, $x_{\mathcal{L}i}$, is the total length of added pipelines multiplied by the capacity of the pipelines per unit energy for the expansion plan i.

4.4.1.7 Energy Diversity

Mexico has been implementing energy reforms and policy to promote energy diversification and increased renewable integration in response to concerns regarding climate change and energy security [3][43]. Ideally a portfolio will have a balance between diversity of energy sources and contributions from renewables [32]. Other studies have stated the importance of energy diversity's role in helping with energy security by minimizing unknown threats [58]. Countries may also be interested in energy diversity due to the possible depletion of energy reserves, uncertainty of future fuel prices, possible disruptions to fuel supply (due to conflict, etc), fuel import dependency and intermittency of electricity supply [32].

A previous study [44] uses the Shannon-Winer Index, Simpsons Index and Sterling Index to look at energy diversity in each state in the United States. For this study the Shannon-Winer Index will be used to measure and compare the energy diversity for all the electricity produced per technology across the entire planning period for each expansion pathway. We use the Shannon-Winer index due to its ability to capture the diversity and balance of the portfolio. Diversity in this case refers to the number of fuel sources used across an expansion pathway and balance has to do with the proportions of the contributions of each fuel source. (The UK uses this index to measure the diversity in their energy sector). The Shannon-Winer Index is expressed in equation (27):

$$x_{Hi} = e^{-\sum_{f=1} p_{fi} \ln p_{fi}} \qquad (27)$$

Where p_{fi} is the proportion of energy produced by fuel source f for expansion plan i, x_{Hi} is the Shannon-Winer Index for expansion plan i. Table 12 gives the Shannon-Winer Index for each of the seven IAM expansion plans in this study. Note that a higher value of the index implies more diversity.

Table 12. Shannon Diversity Index for 2050 Portfolios based on energy production per technology in TWh

Generation Technology	GCAM	IMAGE	LEAP	PHOENIX	POLES	TIAM	EPPA
BIOMASS	1028.4	4147.6	527.0	258.0	1113.7	2102.8	96.4
COAL	533.3	376.9	421.1	1035.1	1084.6	508.7	288.8
SOLAR	281.2	42.4	948.4	0.0	5293.5	8526.8	0.0
GAS	9968.4	8055.8	4426.1	6695.5	12681.4	8334.9	7250.3
GEOTH	419.3	250.4	804.6	231.9	372.2	410.3	0.9
HYDRO	1097.9	1069.6	2356.8	2050.6	1209.2	1096.0	1073.6
NUC	1927.8	1021.2	686.3	686.6	1126.9	1057.0	683.7
OIL	315.8	7.7	392.6	1077.4	373.3	18.6	1.4
WIND	1213.1	707.9	1389.2	3117.9	2111.3	1648.8	225.4
Shannon Index	**4.23**	**3.94**	**6.38**	**4.96**	**4.76**	**4.83**	**2.42**

4.4.2 Weighted Sum Method

With the seven sustainability criteria defined in the previous section it is possible for the decision maker to analyze the tradeoffs between different energy portfolios in the various expansion plans. This allows us to compare the performance of the criteria and check for dominance across the expansion plans. We then aggregate the performance of each expansion plan across criteria with the weighted sum method to obtain an overall sustainability score for each expansion plan with equation (28). This is a similar approach as in [36] and is the most common method used when looking at sustainable energy MCDA [40].

$$S_i = \sum w_j z_{ij} \qquad (28)$$

Where S_i is the sustainability score of expansion plan i, w_j is the weight for the sustainability criteria j, z_{ij} is the normalized score for criteria j and expansion plan i. The normalized scores for each criteria will have values from 0-1, were we consider 1 to be the highest score, being the most favorable, out of the expansion plans and 0 the lowest score. The normalized scores for each criteria are obtained using equations (29) and (30) with the raw sustainability scores x_j:

$$z_{ji} = \frac{x_{ji} - x_{jmin}}{x_{jmax} - x_{jmin}} \qquad where\ \ x_{jmax}\ is\ preferred \qquad (29)$$

$$z_{ji} = \frac{x_{jmax} - x_{ji}}{x_{jmax} - x_{jmin}} \qquad where\ \ x_{jmin}\ is\ preferred \qquad (30)$$

Where x_{ji} is the raw sustainability score for criteria j and expansion plan i, x_{jmax} is the highest raw score for criteria j obtained from all the possible expansion plans and $x_{jmin}$is the lowest raw score for criteria j obtained from all the possible expansion plans. Equation (29) is used when a higher value is preferred such as energy diversity while equation (30) is used when a lower value is preferred such as emissions and water use.

For this study we will analyze the expansion plans considering equal preferences to each criteria. This means that the decision maker is indifferent between moving criteria 1 from its worst to its best or criteria 2 from its worst to its best. Using a similar approach to [41] we use the weighting method from [40] but apply it to expansion plans to the Mexican electrical grid from 2016-2050 rather than to individual generation technologies or portfolios.

4.5 Data

Table 13 provides the fixed and variable components for each criteria based on data from [36][45].

Table 13. Sustainability Criteria Input Data

Generation Technology	Life Cycle GHG		Air Pollution Emissions		Water Consumption		Land Use	
	Fixed kg CO_2eq/ MW	Variable kg CO_2eq/ GWh	Fixed kg/ MW	Variable kg/ GWh	Fixed L/ MW	Variable L/ GWh	Fixed m^2/ MW	Variable m^2/ GWh
Hydro	53	0.0	0.419	0.0	16,587	208	5,715,900	0
Wind	39	0.0	0.345	0.0	11,048	2020	118,522	0
Nuclear	95	0.0	1.672	0.0	16,587	2,415,000	30,747	0
Solar PV	92	0.0	1.528	0.0	72,952	0.0	46,830	0
Natural Gas	0.0	449,000	0.0	988	16,587	815,000	0	310
Oil	0.0	752,000	0.0	2,668	16,587	795,000	0	310
Coal	0.0	768,000	0.0	19,260	16,587	815,000	0	1,480
Coal CCS	0.0	76,800	0.0	19,260	20,000	815,000	0	1,480
Gas CCS	0.0	44,900	0.0	988	20,000	815,000	0	310
CSP	153	0.0	0.722	0	7,000	500	44,676	0
Biopower	0.0	35,000	0.0	1,099	22,000	450,000	0	16,340
Biopower CCS	0.0	3,500	0.0	1,099	25,000	450,000	0	16,340
Oil CCS	0.0	75,200	1090	2,668	20,000	815,000	0	310
Geothermal	49.9	0.0	1.090	0.0	18,000	500,000	549,252	0

Sources: [36,45]

4.5.1 Air Pollution Weights

Figure 30. presents the air pollution weights ω_n for each node, which represent the percentage of the total population at node n.

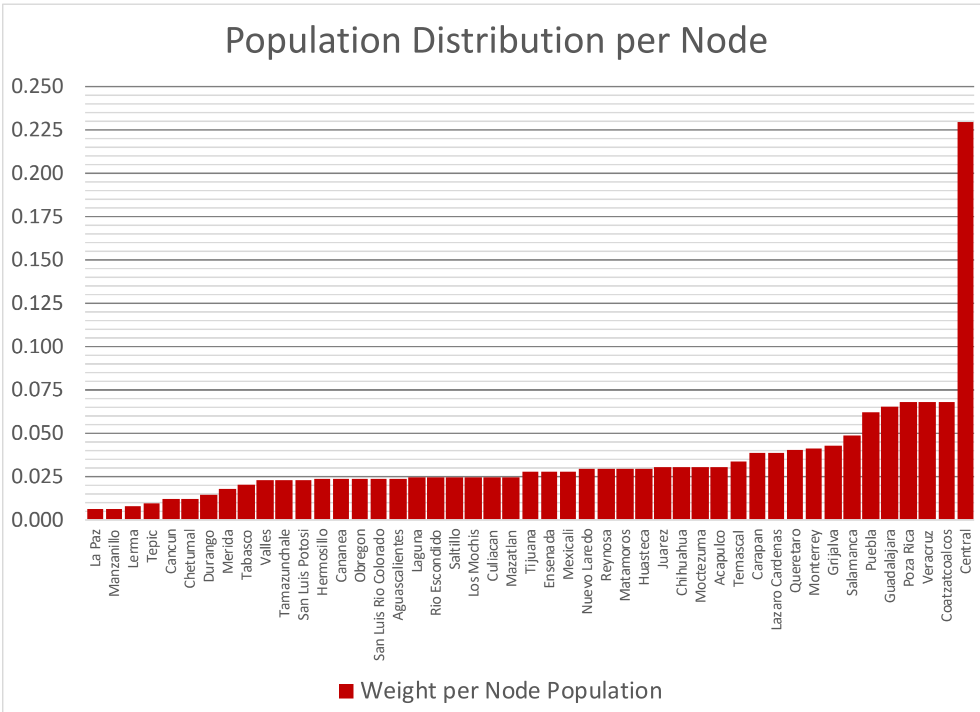


Figure 30. Population Distribution per Node

4.5.2 Water Consumption Weights

Figure 31. presents the water scarcity weights μ_n for all the nodes in the model:

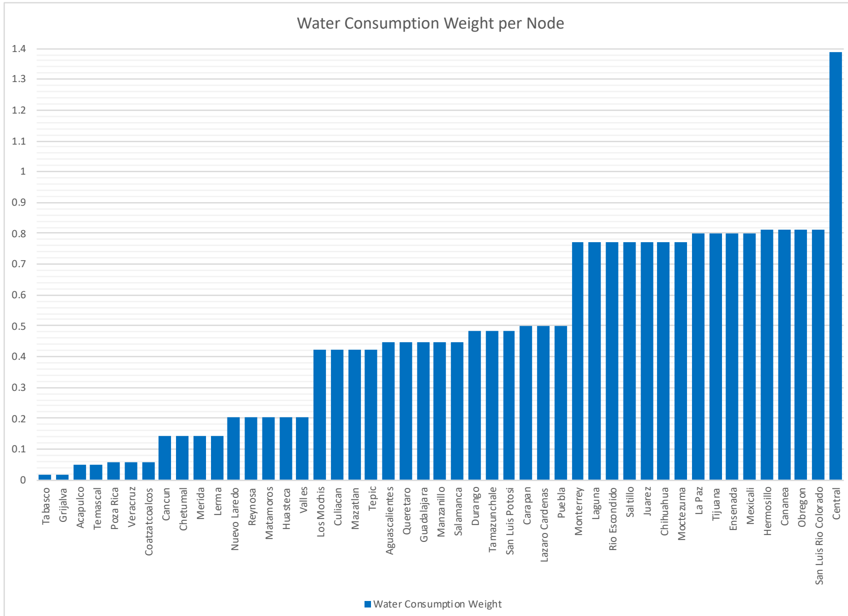


Figure 31. Water Scarcity Weight per Node

In Mexico in 2015 the water use per sector was 14.6% public use, 76.3% agriculture, 4.8% electricity sector excluding hydro generation, and 4.3% industry, with a total water consumption of 266,559 hm^3 [37]. Figure 32. [37] shows the water scarcity for the different hydrological resources in Mexico in 2016. At a national level the water scarcity is considered to be low at 19.2%. But most of Mexico's major population centers are located in regions with a high degree of pressure on its hydrological resources [37].

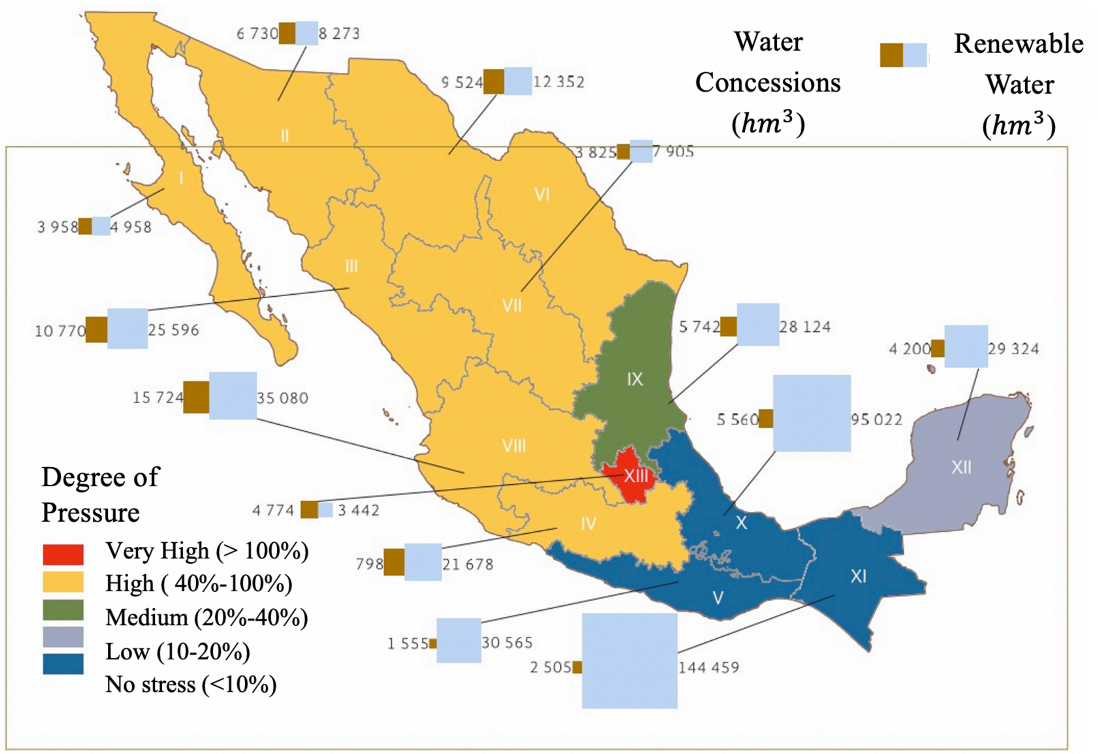


Figure 32. Level of water scarcity in Mexico 2015
Source: SEMARNAT and CONAGUA, "Estadisticas del Agua en Mexico edicion 2016," 2016

Figure 32. was used to calculate the water pressure weights μ_n for each node depending on the area where it is located. This figure helps to highlight areas such as the State of Mexico, containing Mexico City, as critical areas in terms of water use as their water consumption is already greater than the local area's renewable water capacity.

4.6 Results

4.6.1 Expansion Plan Summary

With the necessary criteria defined to evaluate the sustainability of each expansion plan for the Mexican electrical grid from 2016-2050 we present an analysis on sustainability of different development actions. In this section we provide an overview of the IAM expansion plans analyzed in this study, compare the sustainability results for each of the IAM expansion plans, identify critical factors for sustainable development and analyze the equity of each expansion plan. The seven IAM expansion plans are presented in Figure 33 where we can observe the installed capacity and electricity produced per technology in 2050.

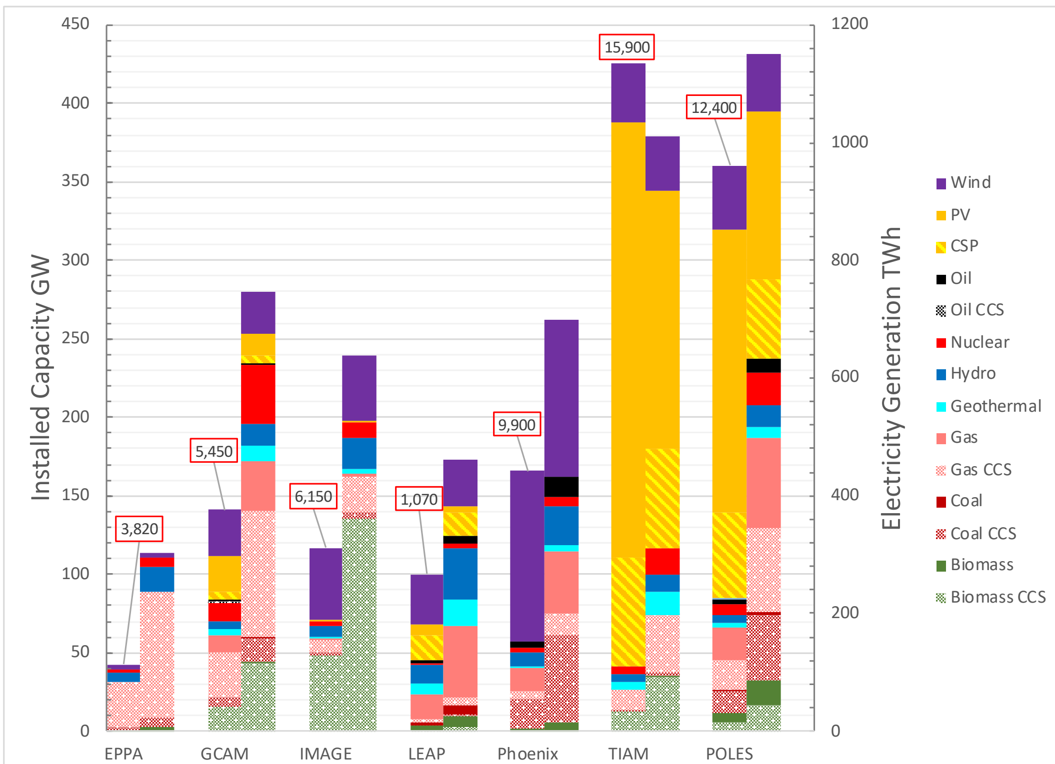


Figure 33. Electricity Generation, Installed Capacity and Transmission added by Scenario for Mexico 2050 50% Abatement

Left bar indicates installed capacity in each IAM scenario and right bar indicates energy produced per technology. The number in a red box above the Installed Capacity of each IAM indicates MW*km of transmission capacity added in each expansion plan.

In this analysis the sustainability of each Expansion Plan (EP) will depend on the expansions to transmission capacity, expansions to installed generation capacity and electricity production per technology across the entire EP from 2016-2050. Figure 34 provides a comparison between the electricity production per technology of the various IAM portfolios in 2050 and the electricity production per technology across the entire planning period. This gives us a better understanding of the overall behavior of the electrical grid. While all the IAM portfolios in 2050 have between 80-100% of electricity production coming from clean energy, in Figure 34 we can see that all IAM portfolios still have a significant contribution from natural gas, ranging from 30-50% of the total electricity produced. This indicates the critical role that natural gas has in the Mexican system during the transition to clean technologies.

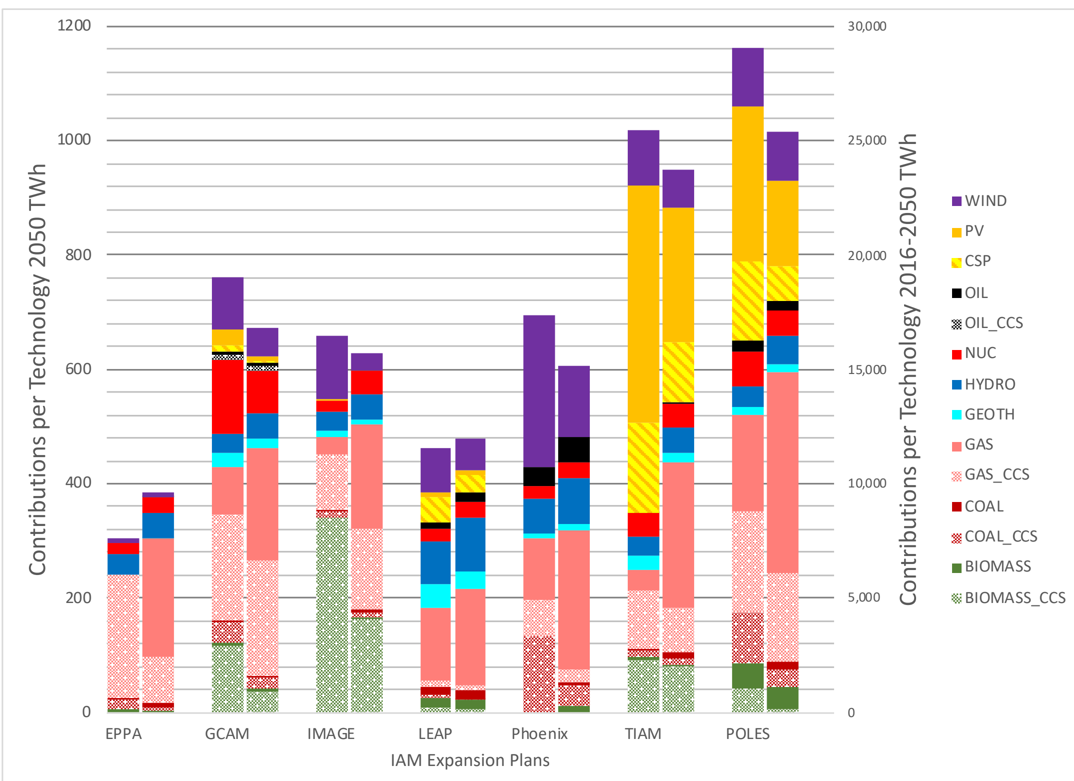


Figure 34. Electricity Generation per technology in each IAM Expansion Plan for Mexico 2016-2050 50% Abatement

Left bar indicates energy produced per technology in 2050 and right bar indicates energy produced per technology from 2016-2050.

4.6.2 Expansion Plan Sustainability Scores

Table 14 presents the EPs ranked from highest to lowest for overall sustainability score as well as presents the raw scores for each sustainability criteria. Figure 35 presents the sustainability score for the EPs considering equal weights for each criteria. The normalized sustainability scores of the data presented in Table 14 are displayed in Figure 36.

Table 14. Per unit of Energy Scores for each Sustainability Criteria for IAM Expansion Plans.

IAM Expansion Plans	Weighted Air Pollution Emissions (kg/GWh)	Weighted Water Use (thousand L/GWh)	Land Use (m^2/ GWh)	Life Cycle GHG Emissions (tons CO2eq/ GWh)	LCOE ($/kWh)	Energy Diversity Total	Cap*m of Pipeline	Sust. Score (0-1)
LEAP	46.1	218.0	3,186	208	0.055	6.38	0.01	.75
TIAM	39.2	211.4	3,328	135	0.073	4.83	0.08	.72
PHOENIX	51.7	292.4	2,615	246	0.040	4.96	0.09	.58
POLES	59.1	317.4	2,352	186	0.051	4.76	0.08	.55
GCAM	53.3	414.5	2,846	155	0.047	4.23	0.14	.49
EPPA	53.9	414.1	2,415	268	0.025	2.42	0.13	.39
IMAGE	53.0	410.6	6,118	150	0.044	3.94	0.24	.31
Max	59.1	414.5	6,118	268	0.073	6.38	0.235	0.76
Min	39.2	211.4	2,352	135	0.025	2.42	0.013	0.31

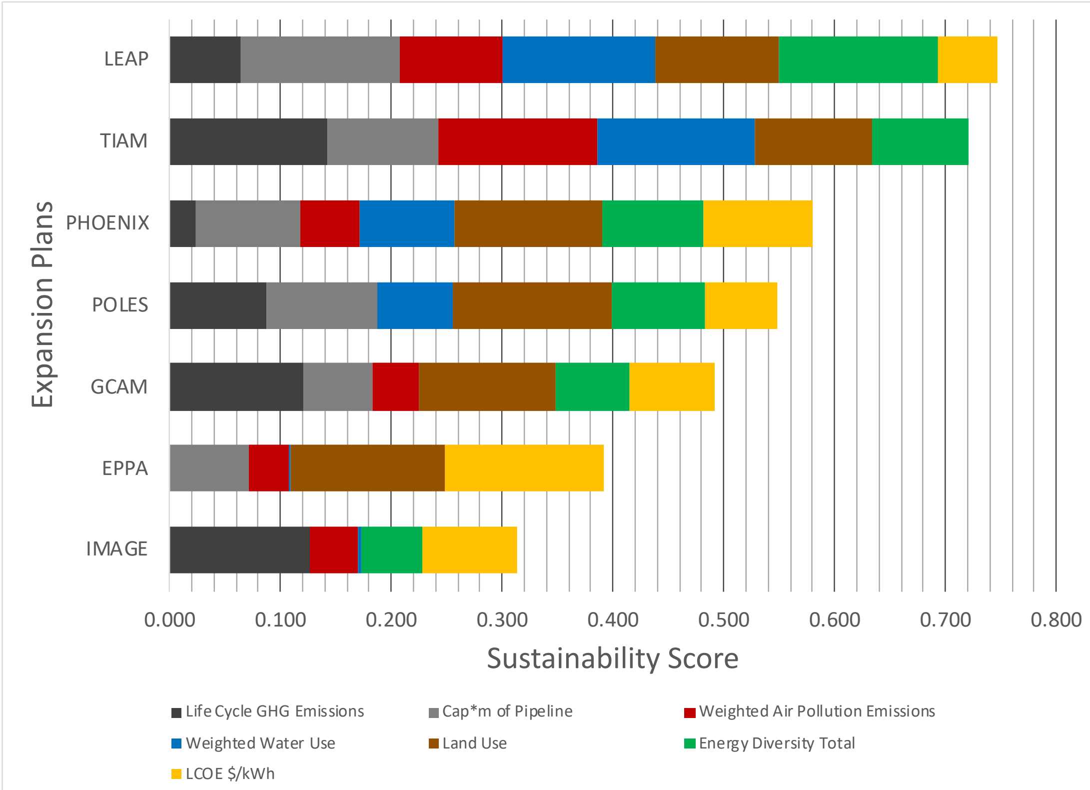


Figure 35.Sustainability Score for Non-Dominated IAM Expansion Plans 2016-2050

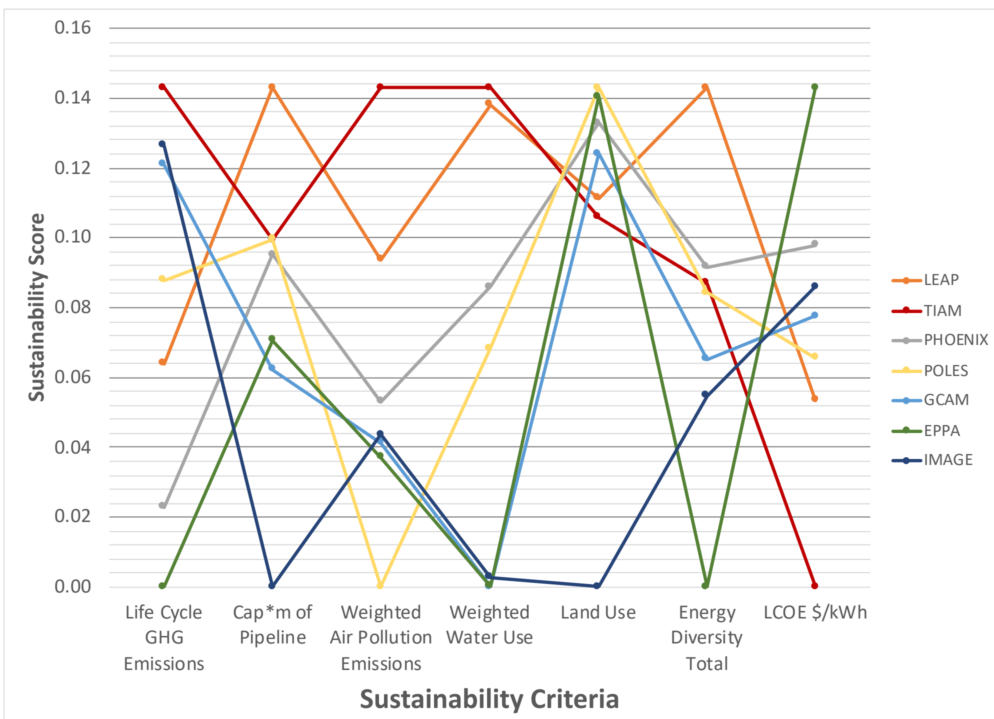


Figure 36. Normalized Sustainability Score for Each Criteria and Expansion Plan Mexico 2016-2050

Of the seven IAM expansion plans, we find that IMAGE, EPPA and GCAM have the lowest overall sustainability score. Of these expansion plans IMAGE and GCAM are nearly dominated if it were not TIAMs high LCOE and land use. The driving factor leading to IMAGE, EPPA and GCAM's low sustainability score when compared to the other IAM expansion plans is their high use of CCS technologies, ranging between 25-50% of total electricity production from 2016-2050. While CCS technologies can be an attractive option to reduce CO_2 emissions without having to drastically change the electricity system, they retain many of the drawbacks of conventional natural gas, coal or oil plants. They do not reduce air pollution emissions of gases such as SO_2, NO_x or particulate matter, they have high water consumption rates compared to renewable technologies, and they have high operational costs due to fuel consumption. Apart from this, CCS technology affects the overall sustainability of an expansion plan directly by requiring the development of large CO_2 transportation and storage networks.

The expansion plans with the highest overall sustainability scores are TIAM and LEAP. We find that these expansion plans benefit from having the low levels of electricity production from CCS technologies, TIAM 18% and LEAP 3%. By having higher levels of renewable and nuclear electricity generation, these expansion plans have lower levels of air pollution emissions and water use and fewer km of pipeline built. LEAP is able to avoid using CCS technologies by having half of its electricity production generated from a balanced mix of renewable technologies, nuclear and hydro. This also helps LEAP to have the highest energy diversity score of any expansion plan. The TIAM expansion plan also manages to incorporate low levels of CCS by generating half of its electricity with renewables and hydro, most of this generated by PV and CSP. The main disadvantage of the TIAM and LEAP expansion plans are their high LCOE due to their investments in high levels of solar. With TIAM's LCOE at $0.073 it is nearly 3 times the cost of the cheapest expansion plan EPPA.

4.6.3 Equity in Sustainability

In this section we provide a comparison of the geographic distribution of total water consumption, air pollution, and land use versus the distribution of poor populations in Mexico per state. Figures 37 and 38 highlight the comparison between the LEAP expansion plan, with the highest sustainability score, and IMAGE with the lowest score. We compare these 2 expansion plans in order to determine how expansion plans with different sustainability scores rate on equity. Table 15 summarizes the results across all of the expansion plans, presenting the percentage of water consumption, air pollution, and land use in states with a poverty rate higher than 50%.

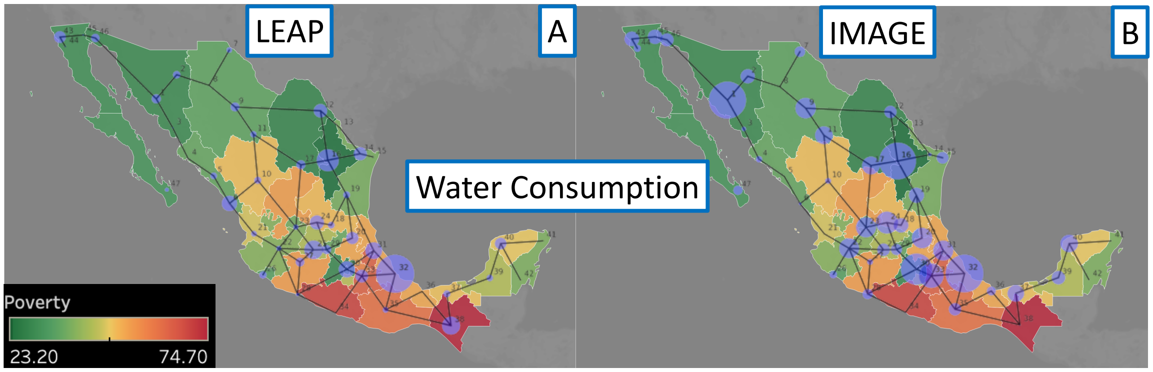


Figure 37. Water Consumption vs Poverty rate per State
Color of the states represent poverty levels, the size of the node represents water consumption at that node

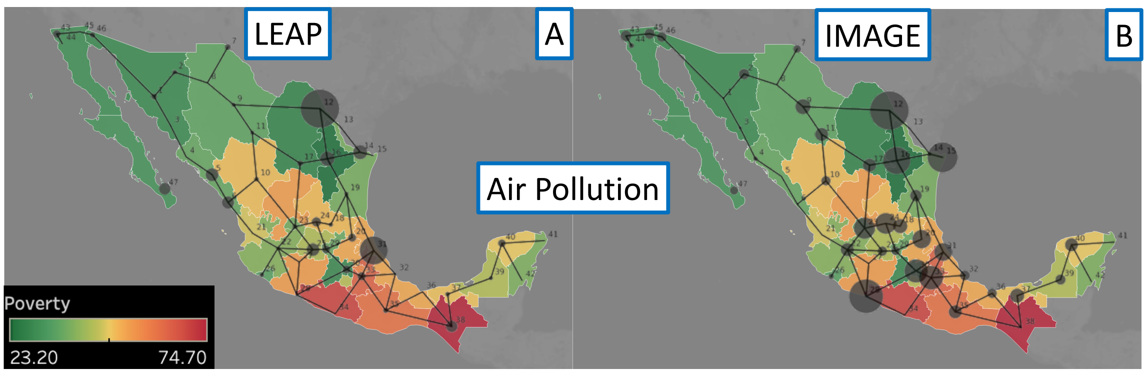


Figure 38. Air Pollution vs Poverty rate per State
Color of the states represent poverty levels, the size of the node represents water consumption at that node

Table 15. Percentage of negative impacts from each criteria in Mexican States with Poverty Rates Greater than 50%
Expansion plans are ordered left to right from highest sustainability score to lowest

Sustainability Criteria	LEAP	TIAM	Phoenix	POLES	GCAM	EPPA	IMAGE
Water Use	49%	45%	35%	37%	14%	34%	18%
Air Pollution	28%	36%	24%	37%	37%	35%	35%
Land Use	41%	25%	29%	29%	31%	45%	22%

Table 15 provides us with a summary of the total water use, air pollution and land use for all the expansion plans in states with a poverty rate greater than 50%. These states account for 37% of the national population. From Table 15 we find that in the LEAP expansion plan 49% of total water use, 28% of air pollution and 41% of land use occur in states with a poverty rate of 50% or higher. This analysis can help us to capture questions of equity that might be lost in a traditional sustainability analysis. For example, we find that while the LEAP expansion plan has the highest sustainability score, IMAGE expansion plan has a smaller relative impact, for water use and land use, on poor states. This is a significant result, as the poor and marginalized communities should not be asked to bear the burden of climate change mitigation efforts. Our goal is to ensure that these mitigation efforts do not disproportionately affect poor communities, as they may be more vulnerable to the exploitation of local water and land resources as well as to health issues related to air pollution.

Figure 39 highlights the geographic distribution of poor states alongside air and water pollution. We have grouped states with similar poverty rates together, creating five groups, each with about the same population (~24 million). These groups are summarized in Table 16. Group 1 represents states with the lowest poverty rates, while Group 5 shows states with the highest. Figure 39 displays a map with these groups of states. We use Figures 40 and 41 to help identify trends in air pollution and water use across groups of states.

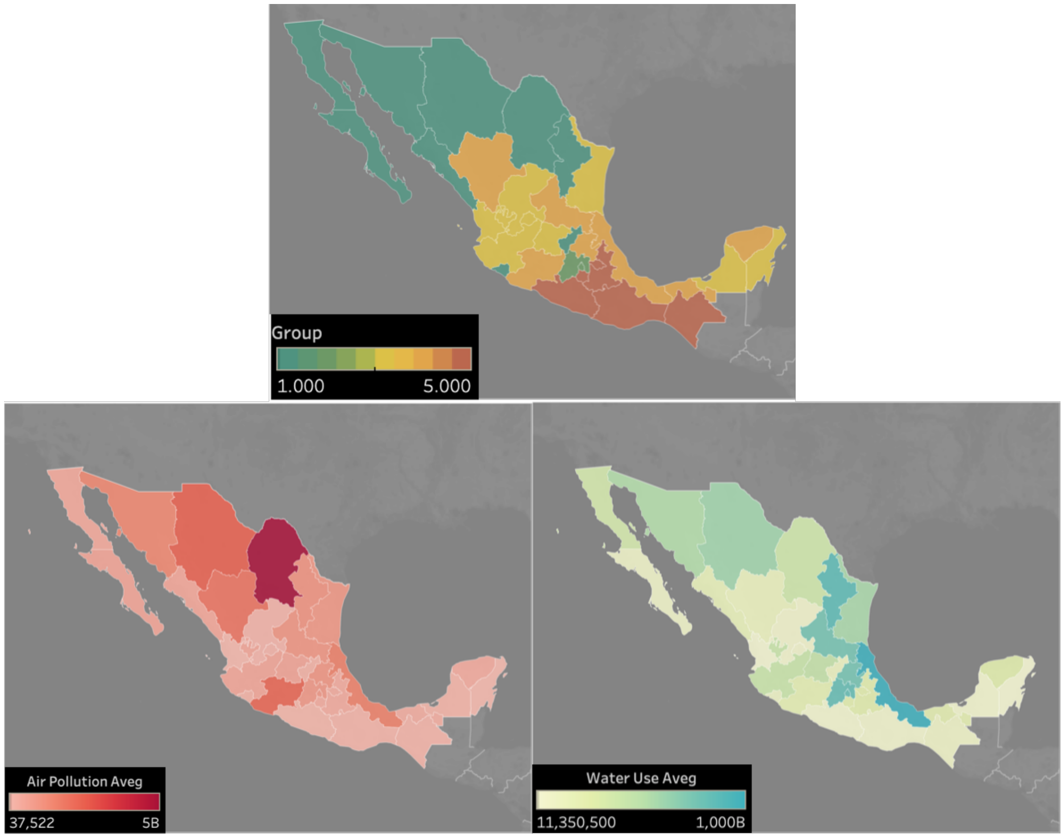


Figure 39. State groups by population and poverty rate and average air pollution and water use per state across expansion plans

Table 16. State groups by population and poverty rate

Group	Poverty Range %	States	Population
1	23.2 - 36.9	Nuevo Leon, Coahuila, Sonora, Baja California, Colima, Chihuahua, Sinaloa, Queretaro	24,225,046
2	28.9	Federal District, Mexico City	24,000,000
3	37.8 - 47.6	Aguascalientes, Tamaulipas, Quinta Roo, Jalisco, Guanajuato, Campeche, Nayarit	23,614,501
4	48.9 - 54.4	Yucatan, Tabasco, Durango, San Luis Potosi, Veracruz, Hidalgo, Zacatecas, Michoacán	24,520,356
5	57.9 – 74.7	Tlaxcala, Oaxaca, Puebla, Guerrero, Chiapas	21,961,678

For all the expansion plans we find a general downward trend in emissions as states get poorer, as shown in Figure 40. This trend can be attributed to the high emissions present in group 1, composed of the wealthiest states. This in turn is mainly driven by the emissions from one state, Coahuila. Across all IAM expansion plans, this state has a high number of coal and gas plants, with some CCS. Coahuila, a largely arid to semi-arid state in northern Mexico, has solar resources but no other renewable sources such as wind, geothermal, or hydro. These deficiencies limit options for development to coal or gas plants which can also be deployed with CCS because of their location near storage sites. It should be noted that deployment of CCS does not affect pollution emissions.

The general downward trend in emissions is broken by a spike in emissions in group 4, composed of the states with the second highest poverty rates. This group demonstrates higher emissions across most states, but particularly in Veracruz, Michoacán, and Durango, largely as a result of limited renewable resources in these areas. Overall Veracruz and Durango have limited renewable resources and are located in areas where CCS is viable. This makes it more likely for CCS plants to be built in these areas across expansion plans which will negatively impact air pollution emissions. Michoacán, located next to the Pacific Ocean and having easier access to transport fuel through the harbor, has the largest coal plant in Mexico in 2016. Additionally, there are only limited geothermal resources in this state, creating another reason for having more development of coal or biomass plants, and eventually higher emission levels.

In general, we see similar behavior in water consumption and air pollution emissions because conventional plants have high levels of air pollution and water consumption. In Figure 13 we see that the dominant group in terms of water use tends to be group 4 with the highest water use of any of the groups. This is driven largely by the state of Veracruz, which has the highest water consumption of any state due to the amount of nuclear energy generated there. Nuclear plants have the highest water use per unit of energy of any generation technology, consuming almost 3 times that of a coal or gas plant. The state of Veracruz always has nuclear plants because the only nuclear plant in Mexico currently (2016) operates in Veracruz.

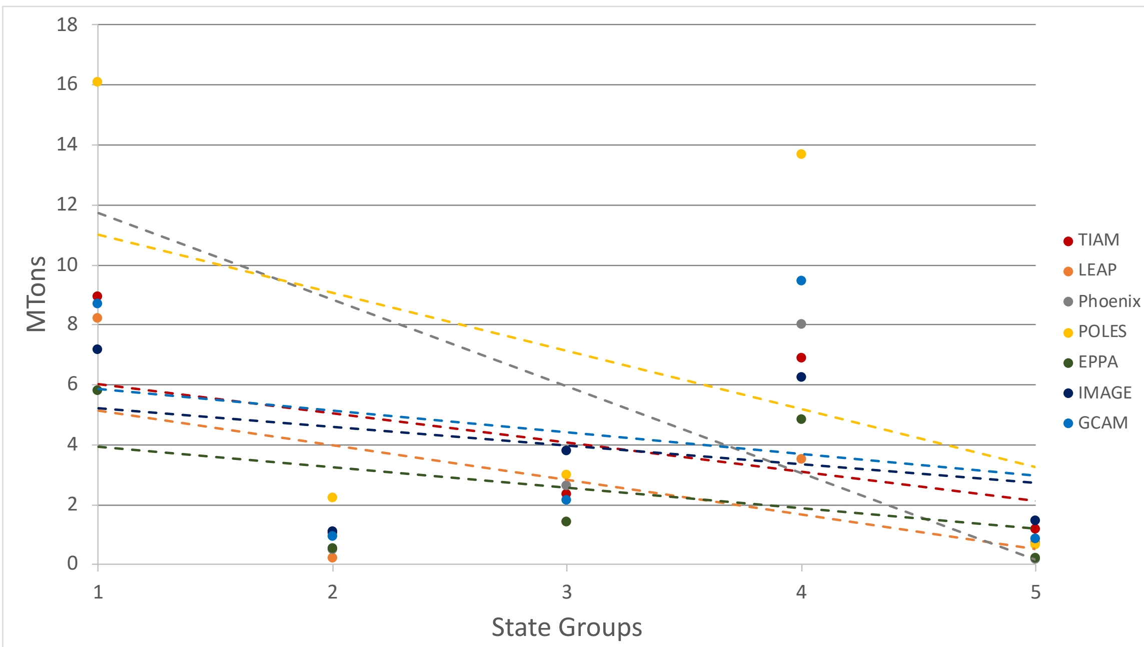


Figure 40. MTons of Air Pollution per Group of States of 24 million people
States in Mexico are in groups of populations of about 24 million, going from states with the lowest to highest poverty rates

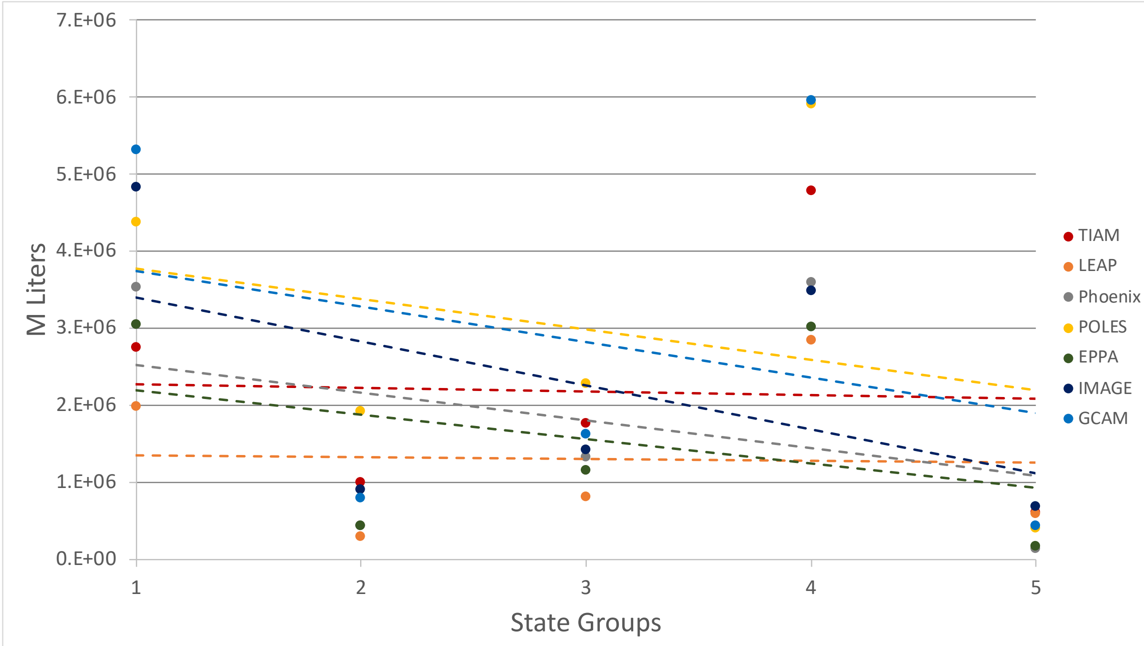


Figure 41. Million Liters per Group of States of 24 million people

States in Mexico are in groups of populations of about 24 million, going from states with the lowest to highest poverty rates

4.7 Limitations

There are several limitations to keep in mind for this study. We use the weighted sum method to calculate the overall sustainability of each expansion plan to the electrical grid. This method allows us to assign different weights to each of the sustainability criteria to reflect different preferences of decision makers. But because we could not perform interviews to capture the preferences of actual decision makers in Mexico, we have applied equal weights to all sustainability criteria. Further work remains to define diverse decision maker preferences and evaluate their effects on rankings in the varied expansion plans. Additionally, the electricity generation characteristics for each of the sustainability criteria obtained from [36, 45] are based on figures for the US. This data might not reflect the same conditions for Mexico.

Incorporating region-specific data could help improve the reliability of the sustainability analysis and ranking to better reflect the Mexican system. Finally, the sustainability and equity results are presented separately, which could make it harder for a decision maker to consider the tradeoffs between various expansion plans.

4.8 Conclusions

In this essay, we provide a unified analysis by using the results from the previous chapters of the dissertation. We use multi criteria decision analysis to evaluate the sustainability and equity of a series of expansion plans for the electricity grid created in Essay 1 and the CCS networks from Essay 2. We use the weighted sum method with seven sustainability criteria to capture environmental, social and economic factors that would be important to the decision maker. With these criteria we evaluate the sustainability of each expansion plan and perform an analysis on equity within each scenario. This allows us to get a better understanding of how sustainability efforts can affect marginalized communities and allows us to plan for development in a way that will distribute its effects in a more sustainable manner.

A novel aspect of our sustainability analysis is that we were able to integrate geographic information into the sustainability and equity analysis of the different expansion plans. The detailed model of the Mexican electrical grid that we used allowed us to take into account information regarding the distribution of resources and population within Mexico. This added another layer of information to our analysis that can be crucial when trying to develop long term sustainable development plans and policy.

In general, we find that for the overall sustainability of each of the expansion plans it is beneficial not to rely heavily on CCS technologies. While CCS generation can be an attractive option to easily lower CO_2 emissions, it has many of the drawbacks regarding air pollution emissions, water use, land use and require the creation of a CO_2 transportation and storage network.

With our equity analysis, we find that none of the expansion plans appears to be particularly regressive. The driving factors for the impacts on equity for the different expansion plans are the portfolio of generation technologies and the geographic constraints related to the different generation technologies within the PEGyT model. For example, while the LEAP expansion plan has the highest sustainability score, it also has the least equitable distribution of water consumption due to its high use of nuclear and hydro generation within poor states in the southeast part of Mexico, as seen in Figure 42 in Appendix. This could be mitigated in part by relying less on these technologies, and instead adding CCS to some of the gas and coal in Veracruz and San Luis Potosi. This would allow the expansion plan to reduce its water consumption footprint in the area. On the other hand, it would increase air pollution emissions and require the development of a larger CCS network. Decision makers must carefully evaluate tradeoffs such as these, taking into account the potential benefits and drawbacks of each development pathway.

This equity and sustainability framework can help us to better understand the macro effects of different development pathways and tradeoffs. In practice this kind of analysis could inform decision makers while they engage and communicate with all the stakeholders. This analysis should be part of an iterative process where models inform decision makers who are communicating with local communities. While at the same time the concerns and needs of the community inform decision makers and the models.

Future work must explore stronger methods for integrating equity into sustainable development and evaluating the effects of various development options on vulnerable communities. We believe it is essential to explicitly address the concerns, needs, and preferences of marginalized communities as part of this process to assist decision makers in adopting better informed and more just and considerate decisions.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

In this dissertation we study a series of energy development pathways for Mexico to reach their long-term climate change goals. The main themes that we address are identifying robust investments across potential development pathways, analyzing the sustainability and equity of different energy portfolios and providing insight for decision makers to inform new energy policy. While the methods presented in this dissertation are applied to the case study of Mexico they can be expanded to other countries and regions to inform national-level climate and energy policy.

In Chapter 2 we provide a decision-relevant multi-model approach to energy planning, developing spatially and temporally detailed expansion plans for the Mexican electrical grid using the results from seven high-level top-down Integrated Assessment Models. We then compare these plans to identify where there is robustness and where there is more flexibility. In contrast to the little robustness in the location of specific generation technologies we find that Mexico has fairly robust near-term investments in transmission expansions. This is encouraging, given that they require long planning horizons and large capital investments.

In Chapter 3 we develop a mixed integer linear programming network expansion model for the capture and storage of CO_2. We then utilize the model to create carbon capture and storage pipeline networks for each of the expansion plans presented in Chapter 2. Ultimately there is little robustness in the connections of the CCS network across the expansion plans. The driving factor behind this is that there is little agreement on the location of specific generation technologies as mentioned in Chapter 2. This implies that there is more uncertainty in the decision-making process for the CCS networks, so tradeoffs have to be considered carefully before committing to a line of action.

Chapter 4 highlights the importance of having multi criteria decision analysis tools to help evaluate the tradeoffs between potential development options. When evaluating each expansion plan, we find that in general pathways with high levels of CCS electricity generation will suffer from low sustainability scores. This is due to the fact that while CCS technologies can help reduce GHG emission they retain many of the drawbacks of conventional power plants such as high-water consumption and air pollution. On the other hand, expansion plans with high levels of CCS are able to maintain low LCOE compared to expansion plans that invest heavily in renewable technologies. These are the kind of tradeoffs that decision makers will have to measure carefully depending on their preferences or the preferences of the various stakeholders involved. We also highlight the importance of studying how various development options may affect vulnerable communities. We find that expansion plans with high sustainability scores do not necessarily have equitable distribution of their effects. This highlights the importance of considering social and local conditions when proposing development plans for energy projects, as well as trying to include stakeholders in the decision-making process from the early stages of the project.

In conclusion we analyzed various development pathways that can help Mexico reach its climate change goals and developed detailed expansion plans for them. With this we were able to identify robust near-term investments for the electricity system and analyze tradeoffs in sustainability. Further work remains in developing better mechanisms for integrating all stakeholders, especially marginalized groups, into the decision-making process to ensure equitable and sustainable energy projects.

5.2 Future Research

For my future work, I intend to build off this thesis to continue to address issues within the field of energy, modeling, equity and policy. The main topics I am interested in tackling are deep decarbonization pathways of the electricity grid; the food-water-energy nexus; and better integration of equity into sustainability analysis of electricity systems.

To continue to analyze decarbonization pathways of the electricity grid to reach climate change goals, we need the ability to confidently model scenarios with high levels of renewable and storage technologies. The intermittent nature of renewables poses a significant challenge for modeling. I would like to further study modeling of the technical and economic performance of intermittent technologies within the grid, especially at high levels of penetration. This would allow to better study scenarios of deep decarbonization.

As these food, water and energy systems grow in complexity it becomes critical to understand their interactions so that we can ensure sustainable and equitable development. Especially with growing concerns regarding to climate change, it will become critical to understand how changing and extreme weather patterns might affect this nexus. I believe that this problem can be tackled with a similar approach to the one presented in this thesis by combining results from various models. Results from high level Integrated Assessment and Climate models can inform detailed electricity models through an iterative process to capture important interactions and limitations within the food, water and energy nexus.

There is a need to better integrate equity analysis into energy planning efforts. It is not enough to find ways to integrate high levels of renewable technologies into the grid. We also have to understand how these projects could affect different social groups. One way in which this can be accomplished is by using an iterative modeling approach with inputs from the various stakeholders. This would help to ensure that all the relevant concerns and needs of stakeholders are addressed. Some criteria that can be used to measure equality in energy planning are accessibility and affordability of electricity, percentage of environmental impacts near marginalized groups, diversity of jobs generated and distribution of electricity consumption across population.

APPENDIX A

IAM DEMDAND CHARACTERISTICS

Poles Demand Characteristics:

POLES Final Demand GWh

Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	13,381.00	14,451.48	15,607.60	16,856.21	18,209.25	19,185.29	20,161.33	21,137.36	22,113.40	23,089.43	24,065.47	25,041.51	26,017.54	26,993.58	31,112.73	37,398.96	43,549.63	49,564.73	52,572.29
Southern Baja California	2,678.00	2,892.24	3,123.62	3,373.51	3,644.30	3,839.64	4,034.98	4,230.32	4,425.65	4,620.99	4,816.33	5,011.67	5,207.01	5,402.35	6,226.73	7,484.82	8,715.78	9,919.61	10,521.53
CENTRAL	54,665.00	59,038.20	63,761.26	68,862.16	74,389.72	78,377.09	82,364.46	86,351.84	90,339.21	94,326.58	98,313.95	102,301.32	106,288.69	110,276.07	127,103.91	152,784.85	177,911.98	202,485.32	214,771.99
North East	51,456.00	55,572.48	60,018.28	64,819.74	70,022.82	73,776.12	77,529.42	81,282.72	85,036.02	88,789.33	92,542.63	96,295.93	100,049.23	103,802.53	119,642.52	143,815.92	167,468.01	190,598.82	202,164.23
North West	22,614.00	24,423.12	26,376.97	28,487.13	30,773.79	32,423.30	34,072.81	35,722.32	37,371.83	39,021.33	40,670.84	42,320.35	43,969.86	45,619.37	52,580.77	63,204.55	73,599.22	83,764.80	88,847.59
North	24,456.00	26,412.48	28,525.48	30,807.52	33,280.44	35,064.30	36,848.17	38,632.04	40,415.91	42,199.78	43,983.65	45,767.51	47,551.38	49,335.25	56,863.68	68,352.81	79,594.17	90,587.78	96,084.58
West	66,465.00	71,782.20	77,524.78	83,726.76	90,447.50	95,295.59	100,143.68	104,991.76	109,839.85	114,687.94	119,536.02	124,384.11	129,232.20	134,080.28	154,540.59	185,765.02	216,316.11	246,193.85	261,132.72
East	47,388.00	51,179.04	55,273.36	59,695.23	64,486.97	67,943.54	71,400.11	74,856.69	78,313.26	81,769.83	85,226.41	88,682.98	92,139.55	95,596.13	110,183.85	132,446.14	154,228.36	175,530.49	186,181.56
Peninsula	11,655.00	12,587.40	13,594.39	14,681.94	15,860.46	16,710.60	17,560.74	18,410.88	19,261.02	20,111.15	20,961.29	21,811.43	22,661.57	23,511.71	27,099.53	32,574.91	37,932.21	43,171.43	45,791.05

POLES Peak Demand MWh/h

Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	2,558.00	2,762.64	2,983.65	3,222.34	3,481.00	3,667.59	3,854.17	4,040.76	4,227.34	4,413.93	4,600.51	4,787.10	4,973.68	5,160.27	5,947.71	7,149.43	8,325.23	9,475.12	10,050.06
Southern Baja California	482.00	520.56	562.20	607.18	655.92	691.08	726.24	761.39	796.55	831.71	866.87	902.03	937.18	972.34	1,120.72	1,347.16	1,568.71	1,785.38	1,893.72
CENTRAL	8,387.00	9,057.96	9,782.60	10,565.20	11,413.27	12,025.04	12,636.80	13,248.57	13,860.33	14,472.09	15,083.86	15,695.62	16,307.39	16,919.15	19,500.97	23,441.08	27,296.22	31,066.39	32,951.48
North East	8,537.00	9,219.96	9,957.56	10,754.16	11,617.40	12,240.10	12,862.81	13,485.51	14,108.22	14,730.92	15,353.63	15,976.34	16,599.04	17,221.75	19,849.74	23,860.32	27,784.41	31,622.01	33,540.81
North West	4,404.00	4,756.32	5,136.83	5,547.77	5,993.09	6,314.33	6,635.56	6,956.80	7,278.04	7,599.27	7,920.51	8,241.75	8,562.98	8,884.22	10,239.93	12,308.87	14,333.20	16,312.91	17,302.77
North	4,165.00	4,498.20	4,858.06	5,246.70	5,667.85	5,971.66	6,275.46	6,579.26	6,883.07	7,186.87	7,490.67	7,794.48	8,098.28	8,402.08	9,684.22	11,640.88	13,555.35	15,427.63	16,363.77
West	9,655.00	10,427.40	11,261.59	12,162.52	13,138.80	13,843.06	14,547.31	15,251.57	15,955.82	16,660.08	17,364.33	18,068.59	18,772.84	19,477.10	22,449.25	26,985.05	31,423.03	35,763.21	37,933.29
East	7,204.00	7,780.32	8,402.75	9,074.97	9,803.41	10,328.89	10,854.36	11,379.83	11,905.31	12,430.78	12,956.26	13,481.73	14,007.20	14,532.68	16,750.33	20,134.68	23,446.04	26,684.43	28,303.62
Peninsula	1,856.00	2,004.48	2,164.84	2,338.03	2,525.70	2,661.08	2,796.46	2,931.84	3,067.22	3,202.60	3,337.98	3,473.36	3,608.74	3,744.12	4,315.46	5,187.39	6,040.51	6,874.83	7,291.99

TIAM Demand Characteristics:

TIAM Final Demand GWh

Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	13,381	13,463	13,545	13,626	13,708	14,531	15,780	17,327	18,875	20,422	21,969	23,516	25,064	26,611	31,207	37,303	41,742	44,523	45,913
Southern Baja California	2,678	2,694	2,711	2,727	2,743	2,908	3,158	3,468	3,777	4,087	4,397	4,706	5,016	5,326	6,246	7,466	8,354	8,911	9,189
CENTRAL	54,665	54,999	55,333	55,667	56,001	59,361	64,466	70,787	77,108	83,429	89,750	96,071	102,392	108,713	127,487	152,395	170,528	181,887	187,567
North East	51,456	51,770	52,085	52,399	52,714	55,876	60,682	66,632	72,581	78,531	84,481	90,431	96,381	102,331	120,003	143,449	160,518	171,210	176,556
North West	22,614	22,752	22,890	23,029	23,167	24,557	26,669	29,283	31,898	34,513	37,128	39,743	42,358	44,973	52,739	63,043	70,545	75,244	77,593
North	24,456	24,605	24,755	24,904	25,054	26,557	28,841	31,669	34,497	37,324	40,152	42,980	45,808	48,636	57,035	68,178	76,291	81,373	83,914
West	66,465	66,871	67,277	67,683	68,089	72,175	78,382	86,067	93,752	101,438	109,123	116,809	124,494	132,179	155,007	185,291	207,338	221,150	228,055
East	47,388	47,678	47,967	48,257	48,546	51,459	55,884	61,364	66,843	72,323	77,802	83,282	88,761	94,241	110,516	132,108	147,827	157,674	162,598
Peninsula	11,655	11,726	11,797	11,869	11,940	12,656	13,745	15,092	16,440	17,788	19,135	20,483	21,831	23,178	27,181	32,492	36,358	38,780	39,991

TIAM Peak Demand MWh/h

Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	2,558	2,574	2,589	2,605	2,621	2,778	3,017	3,312	3,608	3,904	4,200	4,496	4,791	5,087	5,966	7,131	7,980	8,511	8,777
Southern Baja California	482	485	488	491	494	523	568	624	680	736	791	847	903	959	1,124	1,344	1,504	1,604	1,654
CENTRAL	8,387	8,438	8,489	8,541	8,592	9,107	9,891	10,861	11,830	12,800	13,770	14,740	15,709	16,679	19,560	23,381	26,163	27,906	28,778
North East	8,537	8,589	8,641	8,693	8,746	9,270	10,068	11,055	12,042	13,029	14,016	15,003	15,990	16,978	19,910	23,799	26,631	28,405	29,292
North West	4,404	4,431	4,458	4,485	4,512	4,782	5,194	5,703	6,212	6,721	7,231	7,740	8,249	8,758	10,271	12,277	13,738	14,653	15,111
North	4,165	4,190	4,216	4,241	4,267	4,523	4,912	5,393	5,875	6,357	6,838	7,320	7,801	8,283	9,713	11,611	12,993	13,858	14,291
West	9,655	9,714	9,773	9,832	9,891	10,484	11,386	12,502	13,619	14,735	15,852	16,968	18,085	19,201	22,517	26,916	30,119	32,125	33,128
East	7,204	7,248	7,292	7,336	7,380	7,823	8,496	9,329	10,162	10,995	11,828	12,661	13,494	14,327	16,801	20,083	22,473	23,970	24,718
Peninsula	1,856	1,867	1,879	1,890	1,901	2,015	2,189	2,403	2,618	2,833	3,047	3,262	3,476	3,691	4,328	5,174	5,790	6,175	6,368

GCAM Demand Characteristics:

GCAM Final Demand GWh

Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	13,381	13,234	13,088	12,944	12,951	13,516	14,081	14,646	15,210	15,775	16,340	16,905	17,470	18,035	20,277	23,632	27,544	32,014	34,249
Southern Baja California	2,678	2,649	2,619	2,591	2,592	2,705	2,818	2,931	3,044	3,157	3,270	3,383	3,496	3,609	4,058	4,730	5,512	6,407	6,855
CENTRAL	54,665	54,064	53,469	52,881	52,907	55,215	57,523	59,831	62,139	64,447	66,755	69,063	71,371	73,679	82,838	96,542	112,525	130,787	139,918
North East	51,456	50,890	50,330	49,777	49,801	51,974	54,146	56,319	58,491	60,664	62,836	65,009	67,181	69,353	77,975	90,874	105,919	123,109	131,705
North West	22,614	22,365	22,119	21,876	21,887	22,842	23,796	24,751	25,706	26,661	27,615	28,570	29,525	30,480	34,269	39,938	46,550	54,104	57,882
North	24,456	24,187	23,921	23,658	23,670	24,702	25,735	26,767	27,800	28,832	29,865	30,897	31,930	32,962	37,060	43,191	50,341	58,511	62,597
West	66,465	65,734	65,011	64,296	64,328	67,134	69,940	72,746	75,552	78,358	81,165	83,971	86,777	89,583	100,720	117,381	136,814	159,019	170,121
East	47,388	46,867	46,351	45,841	45,864	47,865	49,866	51,866	53,867	55,868	57,868	59,869	61,870	63,871	71,811	83,690	97,545	113,377	121,292
Peninsula	11,655	11,527	11,400	11,275	11,280	11,772	12,264	12,756	13,249	13,741	14,233	14,725	15,217	15,709	17,662	20,583	23,991	27,885	29,832

GCAM Peak Demand MWh/h																			
Area	01__2016	02__2017	03__2018	04__2019	05__2020	06__2021	07__2022	08__2023	09__2024	10__2025	11__2026	12__2027	13__2028	14__2029	15__2030	16__2035	17__2040	18__2045	19__2050
Baja California	2,558	2,530	2,502	2,475	2,476	2,584	2,692	2,800	2,908	3,016	3,124	3,232	3,340	3,448	3,876	4,518	5,265	6,120	6,547
Southern Baja California	482	477	471	466	467	487	507	528	548	568	589	609	629	650	730	851	992	1,153	1,234
CENTRAL	8,387	8,295	8,204	8,113	8,117	8,471	8,826	9,180	9,534	9,888	10,242	10,596	10,950	11,304	12,709	14,812	17,264	20,066	21,467
North East	8,537	8,443	8,350	8,258	8,262	8,623	8,983	9,344	9,704	10,065	10,425	10,785	11,146	11,506	12,937	15,077	17,573	20,425	21,851
North West	4,404	4,356	4,308	4,260	4,262	4,448	4,634	4,820	5,006	5,192	5,378	5,564	5,750	5,936	6,674	7,778	9,065	10,537	11,272
North	4,165	4,119	4,074	4,029	4,031	4,207	4,383	4,559	4,734	4,910	5,086	5,262	5,438	5,614	6,312	7,356	8,573	9,965	10,661
West	9,655	9,549	9,444	9,340	9,345	9,752	10,160	10,567	10,975	11,383	11,790	12,198	12,606	13,013	14,631	17,051	19,874	23,100	24,713
East	7,204	7,125	7,046	6,969	6,972	7,277	7,581	7,885	8,189	8,493	8,797	9,101	9,406	9,710	10,917	12,723	14,829	17,236	18,439
Peninsula	1,856	1,836	1,815	1,795	1,796	1,875	1,953	2,031	2,110	2,188	2,266	2,345	2,423	2,502	2,813	3,278	3,820	4,441	4,751

IMAGE Demand Characteristics:

IMAGE Final Demand GWh																			
Area	01__2016	02__2017	03__2018	04__2019	05__2020	06__2021	07__2022	08__2023	09__2024	10__2025	11__2026	12__2027	13__2028	14__2029	15__2030	16__2035	17__2040	18__2045	19__2050
Baja California	13,381	14,318	15,270	16,033	16,835	16,868	16,901	16,933	16,966	16,999	17,032	17,064	17,097	17,130	18,395	20,861	23,802	27,220	28,928
Southern Baja California	2,678	2,865	3,056	3,209	3,369	3,376	3,382	3,389	3,396	3,402	3,409	3,415	3,422	3,428	3,682	4,175	4,764	5,448	5,790
CENTRAL	54,665	58,492	62,381	65,500	68,775	68,909	69,043	69,177	69,311	69,445	69,579	69,713	69,847	69,981	75,151	85,222	97,239	111,200	118,180
North East	51,456	55,058	58,719	61,655	64,738	64,864	64,990	65,116	65,242	65,368	65,494	65,621	65,747	65,873	70,739	80,219	91,530	104,672	111,243
North West	22,614	24,197	25,806	27,096	28,451	28,507	28,562	28,617	28,673	28,728	28,784	28,839	28,894	28,950	31,089	35,255	40,226	46,001	48,889
North	24,456	26,168	27,908	29,303	30,769	30,829	30,889	30,948	31,008	31,068	31,128	31,188	31,248	31,308	33,621	38,127	43,503	49,748	52,871
West	66,465	71,118	75,847	79,639	83,621	83,784	83,947	84,110	84,273	84,435	84,598	84,761	84,924	85,087	91,373	103,618	118,228	135,203	143,691
East	47,388	50,705	54,077	56,781	59,620	59,736	59,852	59,968	60,084	60,201	60,317	60,433	60,549	60,665	65,147	73,877	84,294	96,397	102,448
Peninsula	11,655	12,471	13,300	13,965	14,663	14,692	14,721	14,749	14,778	14,806	14,835	14,863	14,892	14,920	16,023	18,170	20,732	23,709	25,197

IMAGE Peak Demand MWh/h																			
Area	01__2016	02__2017	03__2018	04__2019	05__2020	06__2021	07__2022	08__2023	09__2024	10__2025	11__2026	12__2027	13__2028	14__2029	15__2030	16__2035	17__2040	18__2045	19__2050
Baja California	2,558	2,737	2,919	3,065	3,218	3,225	3,231	3,237	3,243	3,250	3,256	3,262	3,268	3,275	3,517	3,988	4,550	5,203	5,530
Southern Baja California	482	516	550	578	606	608	609	610	611	612	614	615	616	617	663	751	857	980	1,042
CENTRAL	8,387	8,974	9,571	10,049	10,552	10,572	10,593	10,614	10,634	10,655	10,675	10,696	10,716	10,737	11,530	13,075	14,919	17,061	18,132
North East	8,537	9,135	9,742	10,229	10,741	10,762	10,782	10,803	10,824	10,845	10,866	10,887	10,908	10,929	11,736	13,309	15,186	17,366	18,456
North West	4,404	4,712	5,026	5,277	5,541	5,552	5,562	5,573	5,584	5,595	5,606	5,616	5,627	5,638	6,054	6,866	7,834	8,959	9,521
North	4,165	4,457	4,753	4,991	5,240	5,250	5,260	5,271	5,281	5,291	5,301	5,312	5,322	5,332	5,726	6,493	7,409	8,472	9,004
West	9,655	10,331	11,018	11,569	12,147	12,171	12,194	12,218	12,242	12,265	12,289	12,313	12,336	12,360	13,273	15,052	17,174	19,640	20,873
East	7,204	7,708	8,221	8,632	9,064	9,081	9,099	9,116	9,134	9,152	9,169	9,187	9,205	9,222	9,904	11,231	12,815	14,654	15,574
Peninsula	1,856	1,986	2,118	2,224	2,335	2,340	2,344	2,349	2,353	2,358	2,362	2,367	2,371	2,376	2,552	2,893	3,301	3,775	4,012

LEAP Demand Characteristics:

LEAP Final Demand GWh																			
Area	01__2016	02__2017	03__2018	04__2019	05__2020	06__2021	07__2022	08__2023	09__2024	10__2025	11__2026	12__2027	13__2028	14__2029	15__2030	16__2035	17__2040	18__2045	19__2050
Baja California	13,381	13,101	12,774	12,455	12,081	12,245	12,409	12,573	12,737	12,901	13,065	13,229	13,392	13,556	14,455	15,924	17,727	19,865	20,934
Southern Baja California	2,678	2,622	2,557	2,493	2,418	2,451	2,483	2,516	2,549	2,582	2,615	2,647	2,680	2,713	2,893	3,187	3,548	3,976	4,190
CENTRAL	54,665	53,523	52,185	50,880	49,354	50,024	50,693	51,363	52,033	52,703	53,372	54,042	54,712	55,382	59,052	65,054	72,421	81,153	85,519
North East	51,456	50,381	49,122	47,894	46,457	47,087	47,718	48,348	48,978	49,609	50,239	50,870	51,500	52,130	55,586	61,235	68,170	76,389	80,499
North West	22,614	22,142	21,588	21,048	20,417	20,694	20,971	21,248	21,525	21,802	22,079	22,356	22,633	22,910	24,429	26,912	29,959	33,572	35,378
North	24,456	23,945	23,346	22,763	22,080	22,380	22,679	22,979	23,278	23,578	23,878	24,177	24,477	24,777	26,419	29,104	32,400	36,306	38,260
West	66,465	65,077	63,450	61,863	60,007	60,822	61,636	62,450	63,265	64,079	64,893	65,708	66,522	67,336	71,799	79,097	88,054	98,671	103,980
East	47,388	46,398	45,238	44,107	42,784	43,365	43,945	44,526	45,106	45,687	46,267	46,848	47,429	48,009	51,191	56,394	62,780	70,350	74,135
Peninsula	11,655	11,412	11,126	10,848	10,523	10,665	10,808	10,951	11,094	11,237	11,379	11,522	11,665	11,808	12,590	13,870	15,441	17,302	18,233

LEAP Peak Demand MWh/h																			
Area	01__2016	02__2017	03__2018	04__2019	05__2020	06__2021	07__2022	08__2023	09__2024	10__2025	11__2026	12__2027	13__2028	14__2029	15__2030	16__2035	17__2040	18__2045	19__2050
Baja California	2,558	2,505	2,442	2,381	2,309	2,341	2,372	2,403	2,435	2,466	2,498	2,529	2,560	2,592	2,763	3,044	3,389	3,797	4,002
Southern Baja California	482	472	460	449	435	441	447	453	459	465	471	477	482	488	521	574	639	716	754
CENTRAL	8,387	8,212	8,007	7,806	7,572	7,675	7,778	7,880	7,983	8,086	8,189	8,291	8,394	8,497	9,060	9,981	11,111	12,451	13,121
North East	8,537	8,359	8,150	7,946	7,708	7,812	7,917	8,021	8,126	8,231	8,335	8,440	8,544	8,649	9,222	10,159	11,310	12,674	13,356
North West	4,404	4,312	4,204	4,099	3,976	4,030	4,084	4,138	4,192	4,246	4,300	4,354	4,408	4,462	4,757	5,241	5,834	6,538	6,890
North	4,165	4,078	3,976	3,877	3,760	3,811	3,862	3,913	3,964	4,015	4,067	4,118	4,169	4,220	4,499	4,957	5,518	6,183	6,516
West	9,655	9,453	9,217	8,987	8,717	8,835	8,954	9,072	9,190	9,308	9,427	9,545	9,663	9,782	10,430	11,490	12,791	14,333	15,105
East	7,204	7,054	6,877	6,705	6,504	6,592	6,681	6,769	6,857	6,945	7,034	7,122	7,210	7,298	7,782	8,573	9,544	10,695	11,270
Peninsula	1,856	1,817	1,772	1,728	1,676	1,698	1,721	1,744	1,767	1,789	1,812	1,835	1,858	1,880	2,005	2,209	2,459	2,755	2,904

Phoenix Demand Characteristics:

PHOENIX Final Demand GWh																			
Area	01__2016	02__2017	03__2018	04__2019	05__2020	06__2021	07__2022	08__2023	09__2024	10__2025	11__2026	12__2027	13__2028	14__2029	15__2030	16__2035	17__2040	18__2045	19__2050
Baja California	13,381	13,716	14,058	14,410	14,792	14,886	14,981	15,075	15,170	15,265	15,359	15,454	15,548	15,643	16,929	19,312	23,316	28,940	31,752
Southern Baja California	2,678	2,745	2,814	2,884	2,960	2,979	2,998	3,017	3,036	3,055	3,074	3,093	3,112	3,131	3,388	3,865	4,666	5,792	6,355
CENTRAL	54,665	56,032	57,432	58,868	60,428	60,815	61,201	61,587	61,974	62,360	62,746	63,133	63,519	63,906	69,160	78,897	95,253	118,229	129,717
North East	51,456	52,742	54,061	55,412	56,881	57,245	57,608	57,972	58,336	58,699	59,063	59,427	59,790	60,154	65,100	74,265	89,661	111,289	122,102
North West	22,614	23,179	23,759	24,353	24,998	25,158	25,318	25,478	25,637	25,797	25,957	26,117	26,277	26,437	28,610	32,638	39,405	48,909	53,662
North	24,456	25,067	25,694	26,336	27,034	27,207	27,380	27,553	27,726	27,899	28,071	28,244	28,417	28,590	30,941	35,297	42,614	52,893	58,033
West	66,465	68,127	69,830	71,576	73,472	73,942	74,412	74,882	75,351	75,821	76,291	76,761	77,230	77,700	84,089	95,927	115,814	143,750	157,718
East	47,388	48,573	49,787	51,032	52,384	52,719	53,054	53,389	53,724	54,059	54,394	54,729	55,064	55,398	59,954	68,394	82,573	102,490	112,449
Peninsula	11,655	11,946	12,245	12,551	12,884	12,966	13,049	13,131	13,213	13,296	13,378	13,460	13,543	13,625	14,745	16,821	20,309	25,207	27,657

PHOENIX Peak Demand MWh/h																			
Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	2,558	2,622	2,687	2,755	2,828	2,846	2,864	2,882	2,900	2,918	2,936	2,954	2,972	2,990	3,236	3,692	4,457	5,532	6,070
Southern Baja California	482	494	506	519	533	536	540	543	546	550	553	557	560	563	610	696	840	1,042	1,144
CENTRAL	8,387	8,597	8,812	9,032	9,271	9,331	9,390	9,449	9,508	9,568	9,627	9,686	9,745	9,805	10,611	12,105	14,614	18,139	19,902
North East	8,537	8,750	8,969	9,193	9,437	9,497	9,558	9,618	9,678	9,739	9,799	9,859	9,920	9,980	10,801	12,321	14,876	18,464	20,258
North West	4,404	4,514	4,627	4,743	4,868	4,899	4,931	4,962	4,993	5,024	5,055	5,086	5,117	5,148	5,572	6,356	7,674	9,525	10,450
North	4,165	4,269	4,376	4,485	4,604	4,634	4,663	4,692	4,722	4,751	4,781	4,810	4,840	4,869	5,269	6,011	7,257	9,008	9,883
West	9,655	9,896	10,144	10,397	10,673	10,741	10,809	10,878	10,946	11,014	11,082	11,151	11,219	11,287	12,215	13,935	16,824	20,882	22,911
East	7,204	7,384	7,569	7,758	7,964	8,014	8,065	8,116	8,167	8,218	8,269	8,320	8,371	8,422	9,114	10,397	12,553	15,581	17,095
Peninsula	1,856	1,902	1,950	1,999	2,052	2,065	2,078	2,091	2,104	2,117	2,130	2,144	2,157	2,170	2,348	2,679	3,234	4,014	4,404

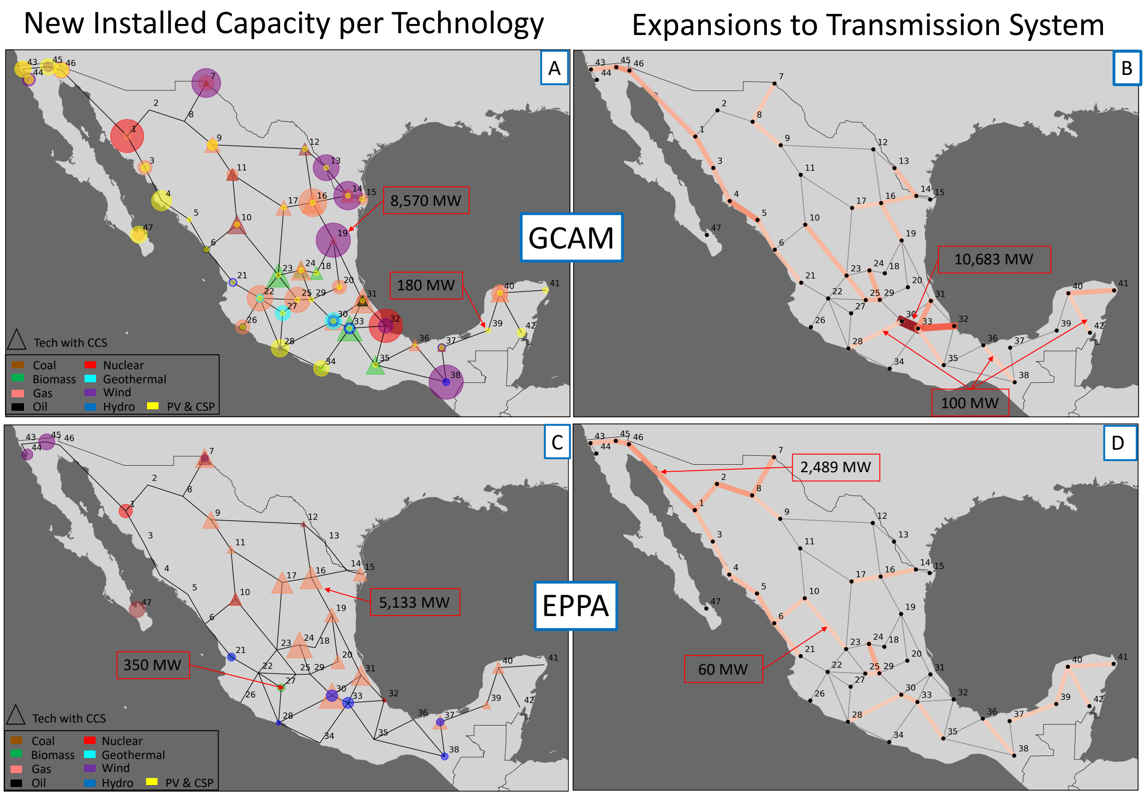
EPPA Demand Characteristics:

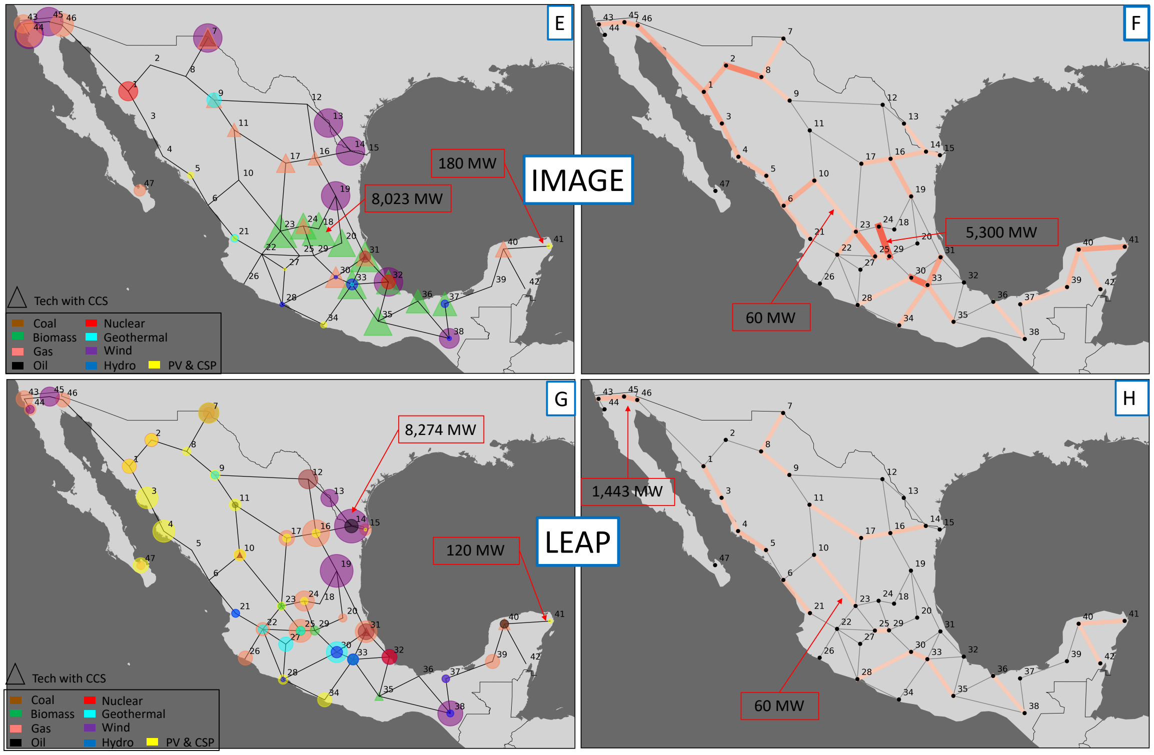
EPPA Final Demand GWh																			
Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	12,223	12,345	12,468	12,593	12,719	12,687	12,656	12,624	12,593	12,561	12,530	12,498	12,467	12,435	12,152	11,647	11,978	13,144	13,727
Southern Baja California	2,446	2,471	2,495	2,520	2,545	2,539	2,533	2,527	2,520	2,514	2,508	2,501	2,495	2,489	2,432	2,331	2,397	2,631	2,747
CENTRAL	49,932	50,432	50,936	51,445	51,960	51,831	51,702	51,574	51,445	51,316	51,187	51,059	50,930	50,801	49,642	47,583	48,934	53,698	56,080
North East	47,001	47,471	47,946	48,425	48,910	48,788	48,667	48,546	48,425	48,304	48,183	48,061	47,940	47,819	46,728	44,789	46,062	50,546	52,787
North West	20,656	20,863	21,071	21,282	21,495	21,442	21,388	21,335	21,282	21,229	21,175	21,122	21,069	21,016	20,536	19,684	20,243	22,214	23,199
North	22,339	22,562	22,788	23,016	23,246	23,188	23,131	23,073	23,015	22,958	22,900	22,843	22,785	22,727	22,209	21,287	21,892	24,023	25,089
West	60,711	61,318	61,931	62,550	63,176	63,019	62,863	62,706	62,550	62,393	62,237	62,080	61,924	61,767	60,358	57,854	59,497	65,289	68,185
East	43,285	43,718	44,155	44,597	45,043	44,931	44,820	44,708	44,596	44,485	44,373	44,262	44,150	44,038	43,034	41,248	42,420	46,550	48,614
Peninsula	10,646	10,752	10,860	10,969	11,078	11,051	11,023	10,996	10,968	10,941	10,914	10,886	10,859	10,831	10,584	10,145	10,433	11,449	11,957

EPPA Peak Demand MWh/h																			
Area	01___2016	02___2017	03___2018	04___2019	05___2020	06___2021	07___2022	08___2023	09___2024	10___2025	11___2026	12___2027	13___2028	14___2029	15___2030	16___2035	17___2040	18___2045	19___2050
Baja California	2,481	2,506	2,531	2,556	2,582	2,575	2,569	2,563	2,556	2,550	2,543	2,537	2,531	2,524	2,467	2,364	2,431	2,668	2,786
Southern Baja California	467	472	477	482	486	485	484	483	482	480	479	478	477	476	465	445	458	503	525
CENTRAL	8,135	8,216	8,298	8,381	8,465	8,444	8,423	8,402	8,381	8,360	8,339	8,318	8,297	8,276	8,087	7,752	7,972	8,748	9,136
North East	8,280	8,363	8,447	8,531	8,616	8,595	8,574	8,552	8,531	8,510	8,488	8,467	8,446	8,424	8,232	7,890	8,115	8,905	9,299
North West	4,271	4,314	4,357	4,401	4,445	4,434	4,423	4,412	4,401	4,390	4,379	4,368	4,357	4,346	4,247	4,070	4,186	4,594	4,797
North	4,040	4,080	4,121	4,162	4,204	4,193	4,183	4,172	4,162	4,152	4,141	4,131	4,120	4,110	4,016	3,850	3,959	4,344	4,537
West	9,364	9,458	9,553	9,648	9,745	9,721	9,696	9,672	9,648	9,624	9,600	9,576	9,552	9,527	9,310	8,924	9,177	10,071	10,517
East	6,987	7,057	7,128	7,199	7,271	7,253	7,235	7,217	7,199	7,181	7,163	7,145	7,127	7,109	6,947	6,658	6,848	7,514	7,847
Peninsula	1,800	1,818	1,836	1,855	1,873	1,869	1,864	1,859	1,855	1,850	1,845	1,841	1,836	1,831	1,790	1,715	1,764	1,936	2,022

APPENDIX B

IAM TO PEGYT RESULTS





E
F
G
H
IMAGE
LEAP
180 MW
8,023 MW
5,300 MW
60 MW
8,274 MW
120 MW
1,443 MW
60 MW
Tech with CCS
Coal
Biomass
Gas
Oil
Nuclear
Geothermal
Wind
Hydro
PV & CSP

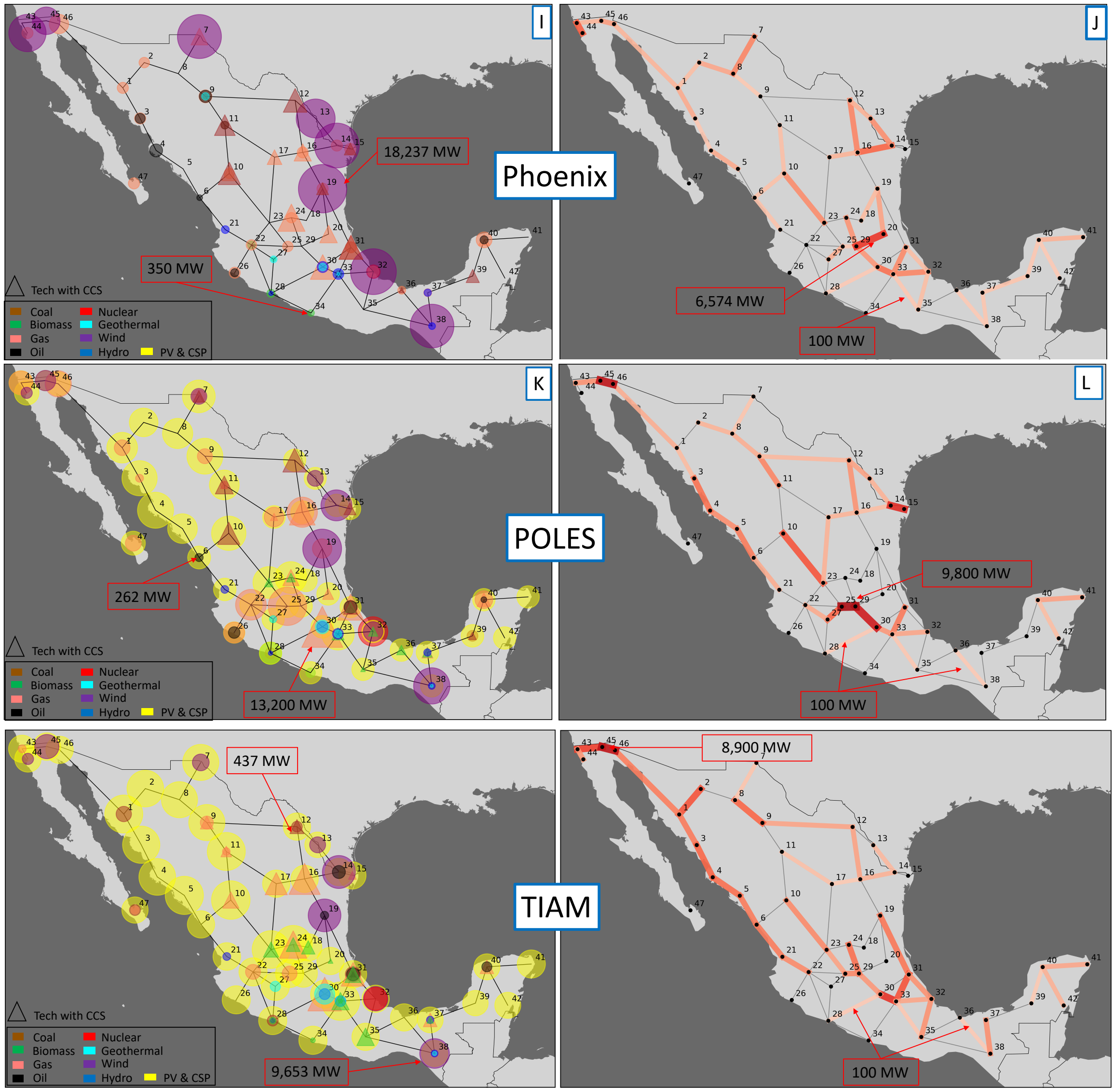


Figure 42. Generation Capacity and Transmission Expansions to the Electrical Grid for all IAMs 2050

Small numbers at each node indicate demand or production points within the system, size of node represents amount of installed capacity, color indicates technology. Grey transmission lines have not been expanded from 2016-2050 and the thickness of the red lines indicate the amount of expansion to each connection. Red boxes indicate amount of installed capacity at node or transmission line.

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